

AUTOMOBILE STEELS



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AUTOMOBILE STEELS

BY

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AND

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Translated from the German by

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Doctor of Engineering

WITH ADDITION OF CHAPTERS ON

S.A.E. STANDARDS ON TEST SPECIMENS AND
STEEL SPECIFICATIONS

AND

FRACTURES OF AUTOMOBILE PARTS

AND NEW AUTHENTIC MATERIAL IN 13 TABLES
FURNISHED BY LEADING AMERICAN AND EUROPEAN
AUTOMOBILE PLANTS

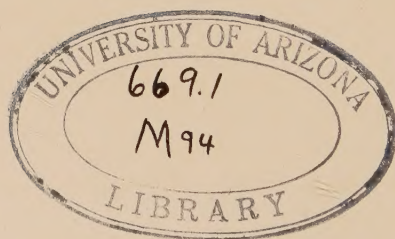
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AUTHORS' PREFACE

The economical and the technical progress made in the manufacture of iron and steel has had a very great influence on the development of the automobile industry. This will be easily understood when it is considered that about 90 per cent of all materials used in automobile production are steels and that it was the introduction and the development of high grade steels that has made the modern automobile possible. In view of this situation, it is really astonishing how little is commonly known about these steels.

The experience of the two authors in the plants of the outstanding manufacturers of high grade steel in Europe and America has shown them that very frequently there is not the exchange of knowledge and experience that there should be between the metallurgist on the one hand and the designer, the manager, the foreman and the workman of the consumer on the other hand. There is need for an exchange of information regarding the stresses that occur in the automobile and the properties of the material. The book, "Praktisches Handbuch über Konstruktionsstahl," by Hüttendirektor O. Thallner, "Bismarckhütte," concerning automobile steels, which was written by one of the outstanding authorities in the field, is now out of date. In the preface to this book it was stated that technical knowledge in that field was frequently kept secret.

These circumstances, together with the constantly increasing importance of the automobile industry, have prompted the publication of this book.

The attitude of secrecy certainly no longer has any place. There was a time when the methods of producing and treating steel were kept secret, but the modern development in this field has brought about an exchange of knowledge and ideas between the technical divisions of the industry. It is important to bring about a similar exchange between the producer and users of automobile steels, in order to remove prejudices and stimulate

cooperation. Many publications now obtainable are too scientific for many of those concerned, some of them deal in too general terms, and most of the articles are too widely scattered to be readily available for reference and use.

The present book was planned to bring this material together in a usable form, and it is the hope of the authors that it shall be a practical manual for the designer, the automobile plant manager, the steel plant manager, the business man, and the mechanic. An attempt was made throughout to make the language so plain that it would be intelligible to everyone, in order that the information given might be available to both the technically trained man and the man on the lathe, who works daily with these automobile steels.

THE AUTHORS.

SIEGBURG (RHEINLAND)

BISMARCKHÜTTE (O. S.)

May, 1927

TRANSLATOR'S PREFACE

In the following translation of the book by Dr. Ing. A. Mueller-Hauff and Dr. Ing. K. Stein, "Autostähle des Welthandels," the translator has kept as close to the original German text as clearness of expression and arrangement would permit. A few paragraphs have been omitted chiefly because they referred to German conditions only, or were of no particular interest to American readers. On the other hand there have been added, thanks to the courtesy of the Society of Automotive Engineers, those chapters on American standards for testing materials and the standardization of steel, that will make the book useful for reference on this subject. It has been possible to add a series of interesting pictures of fractures, through the helpfulness of Dr. M. v. Schwarz, Technische Hochschule, Munich. The tables at the end of the book were revised and brought up to date by the use of information kindly given by some of the leading automobile plants as mentioned in the appendix. Through the excellent cooperation of the authors it has been possible to include the most recent results in connection with those points that were under way at the time the book appeared first in Germany.

For much valuable advice in regard to details the translator is grateful to Reginald L. Rickett, of the University of Michigan, who rewrote the rough translation.

HANS GOLDSCHMIDT.

DETROIT, MICHIGAN,
October, 1929

CONTENTS

	PAGE
INTRODUCTION.....	1
CHAPTER I: TEST OF MATERIALS	
CONSTITUENTS OF STEEL.....	3
THE COMMON STATIC TENSILE STRENGTH TEST.....	4
The Elastic Limit; The Proportional Limit; The Yield Point; The Point of Rupture; The Elongation; The Reduction of Area; The Rupture Work, Stress-Elongation Diagram; The Test Specimen, The American Standard Test Specimen; The German Standard Test Specimen.	
THE SUDDEN LOAD TEST.....	14
The Calculation of Rupture Force and of Rupture Work.	
THE IMPACT TEST.....	15
Calculation of the Height of Fall and Rise; The Test Specimen; The Working Constant and Working Velocity.	
THE FATIGUE TEST.....	19
The Krupp Fatigue Testing Machine; Characteristic of Fatigue Break.	
THE HARDNESS TEST.....	22
The Brinell Test; Brinell Hardness and Tensile Strength; Other Tests; The Method of Herbert, Shore Scleroscope, The Scratch Method.	
THE BENDING TEST.....	26
THE FORGING TEST.....	26
THE WELDING TEST.....	26
THE MULTIPLE BENDING TEST.....	26
THE TORSION TEST.....	27
THE DUCTILITY TEST.....	27
CHAPTER II: METALLOGRAPHY	
SOLIDIFICATION.....	31
AUSTENITE.....	31
THE EUTECTIC OF IRON-CARBON ALLOY: LEDEBURITE.....	32
THE PRODUCTS OF DECOMPOSITION OF AUSTENITE ON SLOW COOLING...	34
THE EUTECTOID: PEARLITE.....	34

	PAGE
THE IRON-CARBON DIAGRAM.....	36
THE PRODUCTS OF DECOMPOSITION OF AUSTENITE ON FAST COOLING MARTENSITE, TROOSTITE, SORBITE.....	38
COARSE GRAIN.....	41
RECRYSTALLIZATION.....	42
THE INFLUENCE OF MANGANESE, NICKEL, CHROMIUM AND TUNGSTEN ON THE FORMATION OF THE MICROSTRUCTURE.....	42
 CHAPTER III: THE MANUFACTURE OF AUTOMOBILE STEELS	
THE TREATMENT IN THE MELTING APPARATUS.....	44
Open-hearth and Electric Furnace; Deoxydation; The Slag.	
THE POURING OF THE STEEL.....	46
Solidification; Segregation, Shrinkage Cavities or Pipes; Gas- blisters, Gas-Segregation; Segregation and Testing; Form and Size of the Ingot.	
THE FORGING AND ROLLING.....	52
The Influence of Temperature on Forging and Rolling; Drop Forging; Testing of the Bars.	
ANNEALING.....	56
WELDING.....	58
COLD DRAWING, COLD ROLLING: ITS ADVANTAGES AND DISADVANTAGES.	59
STRIPS.....	63
RECRYSTALLIZATION.....	63
MACHINABILITY OF STEEL.....	63

CHAPTER IV: THE AUTOMOBILE STEELS

1. COMMON CARBON STEEL.....	65
Screw Steel; Steel for Sheet Metal; Steel for Deep Drawing Sheet Metal; Steel for Cold Rolled Strips; Steel for Wire; Steel for Pressed Nuts; Silicon Steel; Steel Castings; Annealing of Steel Castings; The German Standards for Steel Castings; The American Standards for Steel Castings; Alloyed Steel Castings, Forged Steel Castings.	
2. CASE-HARDENING STEEL.....	75
Effect of Case-hardening; Test of Surface Hardness and Core Tough- ness; The Straight Carbon Case-hardening Steel; Nickel Case- hardening Steel; Chromium Case-hardening Steel; Chromium- Nickel Case-hardening Steel.	
3. CASE-HARDENING PROCESS.....	82
The Carburizers; Carburizing Temperature and Time; Double- hardening Treatment; Baths for Case-hardening; Failures in Case- hardening; Nitriding.	

	PAGE
4. THE HEAT-TREATING STEELS.....	91
The Straight Carbon Heat-treating Steels; The Nickel Heat-treating Steels; The Chromium Heat-treating Steels; The Vanadium Heat-treating Steels; The Chromium-Nickel Heat-treating Steels; The Universal Steels; The Air-hardening Steels; The Oil-hardening Steels; The Molybdenum Steels; The Heat Treatment; Hardening Temperature; Annealing Brittleness.	
5. THE SPRING STEELS.....	116
The Straight Carbon Spring Steel; The Manganese Spring Steels; The Manganese Silicon Spring Steels; The Chromium Silicon Spring Steels; The Manufacture and Heat Treatment of Springs.	
6. THE BALL-BEARING STEELS.....	123
The Manufacture of Ball Bearing Steel; Chromium Steels for Balls and Rings; The Hardening and Testing of the Parts; Failures: Soft Skin and Unequal Hardness.	
7. THE MAGNET STEELS.....	127
Magnetism; D.C. Magnets; A.C. Magnets; Hysteresis; Permanent Magnets Tungstenl Magnets; Chromium Magnets; Cobalt Magnets.	
8. THE VALVE STEELS.....	133
The Requirements for Valves; Chromium Steels for Valves; Tests with Various Materials; Chromium-Silicon Steels.	
9. THE STAINLESS STEELS.....	142
Explanation of Rusting; Analysis; the Manufacturing of Stainless Steels; Hardening of Parts from Stainless Steel; Grinding and Polishing of Parts from Stainless Steel; High Alloy Chromium-Nickel Steels; Other Ways of Rust Proofing; Chromium Plating for Wear Resistance.	
CHAPTER V: PRINCIPLES FOR THE SELECTION OF STEELS FOR THE VARIOUS PARTS OF AUTOMOBILES	
	148
CHAPTER VI: THE STANDARDIZATION OF AUTOMOBILE STEELS	
THE AMERICAN STANDARDS.....	153
Heat Treat Charts.	
THE GERMAN STANDARDS.....	163
Standards for Alloyed Steel.	
CHAPTER VII: FAILURES	
	168
CHAPTER VIII: STEEL ANALYSIS OF AUTOMOBILE PARTS	
	177
BIBLIOGRAPHY.....	195
INDEX	199

AUTOMOBILE STEELS

INTRODUCTION

The production of steel by the open-hearth and bessemer processes began about 1855. Although these processes had many advantages, both in the quality and the quantity of the metal produced, as compared to the wrought-iron manufacturing process, no further progress was made in improving the quality until the end of the last century. For tool steels the method of melting in crucibles remained efficient enough, and for all other purposes the open-hearth or bessemer product in its first form proved to meet the demands.

The reason for this situation was that, for the heavy parts of machines and for locomotives, the common machine steel was good enough and there was little need for high-class steel. The development of the automobile, however, which requires the transmission of large forces through light members, led to a complete change in the demands. It was necessary to produce lighter parts from steel with higher properties and this led to the development of refined steels, which for that reason may be called automobile steels.

Automobile steels were first produced in crucibles, but on account of the high cost of this process it was replaced during the first part of this century by the electric furnace process. This process has experienced considerable growth and improvement, until it has finally reached its present-day importance and world-wide use. During the same time the technique of the open-hearth process was materially improved, so that now a large number of automobile steels are produced by this process.

Improvement in automobiles, not only of the engine, but of the whole car, is based less upon change in design than upon improvement in the steel used. In hardly any other case has the influence of materials been so great. The use of refined steels has resulted

in reducing the weight of transmission and chassis nearly one half, resulting in lower cost, better design, and an improvement in the whole driving quality.

Although refined steels play an important part in the manufacture of automobiles on account of the increasing demands in performance, we frequently find among people engaged in this business a lack of knowledge of the chemical, physical, and thermal properties of automobile steels and the range of their use. The designer knows that the use of the most suitable material is necessary to obtain the highest quality in the automobile. Only the choice of proper material will make a design ready to go into production. The designer aims to attain the least possible weight combined with highest stress and smallest area. The steel must stand the various and changing stresses of sudden loads, vibrations, and wear; otherwise, in spite of careful calculations, the assumed safety figures will not be correct. On inspection of various automobile plants much unsuitable or poor quality material was frequently found and often the desire was expressed of having a still better exchange of experiences between the steel producer and the consumer.

Many failures were due to a lack of knowledge of material, many to difficulties in the heat treatment. Frequently too expensive a steel was used, or high-grade steel was not used to full advantage because its properties were not known, and an unnecessary increase in cost was the result.

A comparison of German and American makes shows that in America less high grade steels are used, but their properties are improved by heat treatment. In that comparison it is necessary to take into consideration the poorer condition of the roads in Germany, which necessitates the use of better steel. The rapid progress in motorizing Germany, as well as the need to obtain the most economical production, will result in changing to the safest, but also less expensive, material.

CHAPTER I

TEST OF MATERIALS

Constituents of Steel.—Technical iron, usually called steel, contains not only pure iron (Fe), but a large number of other elements, partly unintentionally present, partly added to improve the mechanical properties. The most important of these elements is carbon (C), of which steel contains up to 1.5%, and pig iron and cast iron contain up to 4%. The second element which imparts desirable properties is manganese (Mn). Detrimental elements are phosphorus (P), which causes steel to be brittle when cold, and sulphur (S), which causes it to be brittle when hot. These two elements are kept as low as possible; but bessemer steel will contain 0.05–0.08%, open-hearth steel 0.02–0.05%, and electric furnace steel 0.01–0.02%. Good automobile steel should contain not more than 0.04%. Beside these elements there are unintentionally present copper (Cu), sometimes arsenic (As), antimony (Sb), tin (Sn), and various gases. The following elements are added with the purpose of obtaining special properties: Carbon (C), manganese (Mn), silicon (Si), chromium (Cr), nickel (Ni), tungsten (W), vanadium (V), molybdenum (Mo), and cobalt (Co).

The various kinds of steel may be divided into two groups: tool steel, and structural and machine steel. The latter is used for beams, crankshafts, axles, gears, etc. Tool steel is used for such tools as lathe tools, drills, cutters, etc. Steel used for machinery should have great toughness in addition to high strength. In case overloading occurs, it should be indicated by deformation before breakage takes place. Steel to be used in machine construction must not be brittle and under any circumstances should “bend rather than break.”

The strength and toughness of the material is determined by means of the tensile strength test. Complementary tests are frequently made such as impact tests, sudden load tests, and Brinell hardness measurements.

THE COMMON STATIC TENSILE STRENGTH TEST

The test piece is subjected to a slowly increasing load in a testing machine until it deforms and then breaks; and the deformation is observed. The action of the testing machine causes the piece to elongate and at the same time to be reduced in cross-sectional area. Except in scientific research, the unit forces acting on the test bar are always referred to the original cross-sectional area of the piece, because only this area can be used by the designer in his calculations. The total load, divided by the original cross-sectional area of the piece gives the unit stress.

Elongation.—Under stress a piece will suffer an elongation, which will usually consist of an elastic and a permanent deformation.

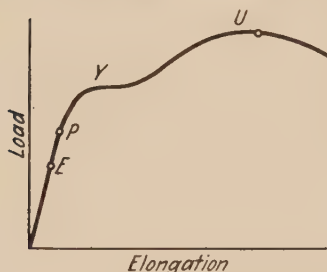


FIG. 1.—Stress-elongation diagram.

If the load is removed, the piece will become shorter again to an extent which corresponds to the elastic deformation, but will not return to its original length. This permanent elongation results from the plastic deformation. The ratio of the permanent to the elastic deformation will vary according to the material and to the stress. If we measure during the test the elongation and the load, we can draw the stress elongation diagram, showing as abscissas the unit deformation and as ordinates the unit stresses. Figure 1 is the stress-deformation diagram or rupture diagram of a soft steel, showing the most important stress points.

Elastic Limit, Proportional Limit, Yield Point.—If the piece is subjected to stresses that are below the point *E* on the diagram and the load is taken off again, we will not find any permanent elongation. Since the piece may be considered to be practically perfectly elastic up to this point, we call it the Elastic Limit. Stresses up to those at point *P* result in a permanent deformation that is proportional to the stress, and this point is called the Proportional Limit. When the load is increased beyond its value at the proportional limit, the deformation will increase at a greater rate than the unit stress, until at a point *Y* the piece will continue to elongate under a constant, or even decreasing, load. This

point, where the material begins to flow, is called the Yield Point. When the flow has ceased, it will be necessary to increase the load to cause further deformation, but small increments will be sufficient to cause large deformations.

Point of Rupture.—Finally as the load is decreased, the piece, originally cylindrical, becomes reduced in cross-sectional area and finally breaks, at a point where this reduction in area is the greatest.

The physical data are taken from the test as follows:

The **elastic limit** is that point where the permanent deformation reaches a measurable value. It is determined by starting with a small load and increasing the load in steps, the load being reduced to the original value after each step, until a permanent deformation is recorded. In order to avoid any personal judgment, the elastic limit will be considered as reached when the permanent deformation has reached 0.003 per cent of the gage length. These small values can be measured only by an apparatus based upon the optical principle.

The **proportional limit** is the point up to which equal increments of stress produce equal elongation. This point is determined by measuring the elongation for equal load increments and is considered to be the point at which the elongation for 1500 lb. per sq. in. becomes more than 0.005% of the gage length greater than the average preceding elongations. Since the determination of the elastic and proportional limits takes considerable time and is feasible only with sensitive instruments, they are often omitted in practical tests.

At the **yield point** considerable increase in deformation takes place without increasing the load and may even continue if the load is decreased. This point will be observed as a sudden drop of the scale beam or the dial. The stress at which this yielding starts is called the *upper yield point*; that stress, which is just sufficient to continue the yielding, is the *lower yield point*. In passing through the yield point the surface of the test piece undergoes a change. On common rolled test pieces the scale breaks off, and on machined and ground pieces the surface becomes dull. If no sharp yield point is observed, the yield point is taken to be that point where the permanent deformation becomes 0.2% of the gage length. When this is done, it should be so stated in the test record, to avoid confusion.

In calculating the strength the largest load, U , and the original cross-sectional area are used. Material with a large reduction of area will show this maximum load long before rupture, since the reduction in area of the specimen will cause the breaking load to be much less than the maximum load.

ELONGATION

The elongation is indirectly measured on the broken test piece, so that only the permanent elongation can be exactly determined. The elongation per unit of original length will vary over the gage length, since the portions having the greatest reduction of cross-sectional area will undergo the greatest elongation. The test piece is marked with a marking machine before

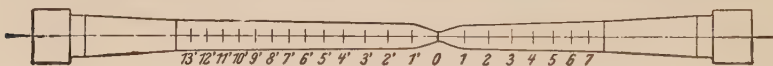


FIG. 2.—Test specimen.

testing and the elongations determined from the difference in distance between the gage marks on the original, unloaded piece and the piece when ruptured. Figures 2 and 3 show a broken test piece with the marks and demonstrate clearly that the elongation

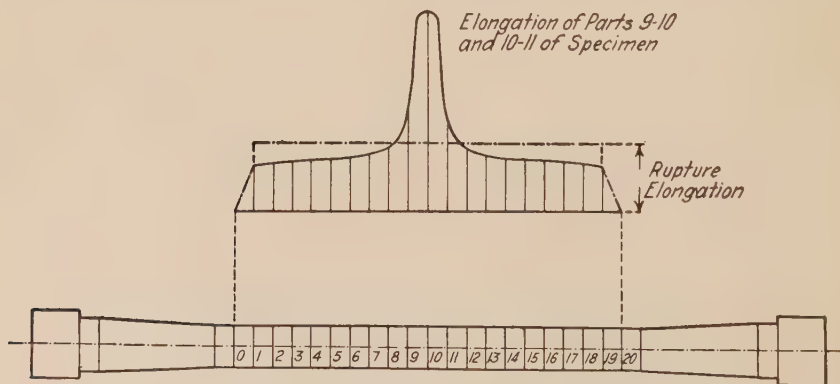


FIG. 3.—Test specimen and elongation diagram.

is greater at the reduced section. Since the elongation is determined from a definite part of the length of the specimen, it will vary with variations in the location of the rupture within this measured length. Figure 3 shows the percentage elongation

between the gage marks of a piece. The smaller, the original gage length, the larger is the percentage elongation. The figure also shows that correct values of elongation are obtained only when rupture occurs within the middle third of the piece. If the piece breaks near the end, it is possible to calculate the probable elongation which the specimen would have shown if broken near the middle, but for exact measurements it is safer to make a new test. Standard gage lengths for determining elongation are always given in terms of the original cross-sectional area. The standard length varies in different countries, the standard lengths for the United States and various European countries being given in Table I.¹

TABLE I.—STANDARD GAGE LENGTHS FOR STEEL TEST SPECIMENS

Country	Gage—Length	Standard Test Specimen
Germany.....	$11.3 \sqrt{A} = 10 d$ $5.65 \text{ " } = 5 \text{ "}$ $2.825 \text{ " } = 2.5 \text{ "}$	20 mm. diameter $\times$ 200 mm.
Austrian Railroad...	$9.0 \text{ " } = 8 \text{ "}$	25 " " $\times$ 200 "
France.....	$8.2 \text{ " } = 7.25 \text{ "}$	13.8 " " $\times$ 100 "
Great Britain.....	$4.0 \text{ " } = 3.55 \text{ "}$	$\frac{3}{16}$ in. " $\times$ 2 in.
Registro Italiano..	$9.0 \text{ " } = 8.0 \text{ "}$ $4.5 \text{ " } = 4.0 \text{ "}$	
Norske Veritas....	$9.0 \text{ " } = 8.0 \text{ "}$ $4.5 \text{ " } = 4.0 \text{ "}$	
United States.....	$4.5 \text{ " } = 4.0 \text{ "}$	0.505 " " $\times$ 2 "

A = cross-sectional area of test specimen.

d = diameter of test specimen.

To obtain the value of the elongation, the two halves of the test piece are pressed together, but not so hard that they will buckle. The elongation of each half may also be determined individually. It is advisable to determine the elongation for two gage lengths, which will not be difficult if a marking machine is used.

For soft steel it is advisable to use a gage length 5 times the diameter, because this material often shows two sections of large reduction of area and the extension would be too great. After-

¹ Sachs-Fick, Der Zugversuch.

ward it is possible to convert the elongation to any gage length by calculation, using the formula:

$$D = A + B/\sqrt{M}$$

where A and B are constants of the material;

D is the elongation;

M is the gage length.

If the elongation for a test piece has been determined for two gage lengths, it is possible to calculate the constants A and B and thus to find the elongations for all other gage lengths.

Example: The first test showed the elongation for a gage length of $10 \times d$ to be 18 per cent; and for a gage length of $5 \times d$ to be 25%. What is the elongation for a gage length of $9.0\sqrt{A} = 8 \times d$?

d is the diameter of the test piece.

Solution:

Using the formula $D = A + B/\sqrt{M}$ gives

$$18 = A + B/\sqrt{10},$$

$$25 = A + B/\sqrt{5},$$

The two equations give values: $A = 1.1$ and $B = 53.5$.

Substituting these values in the formula will give the elongation D for a gage length of $8 \times d$:

$$D = 1.1 + 53.5/\sqrt{8} = 1.1 + 18.9 = 20.0.$$

Thus the elongation for the gage length $9.0\sqrt{A} = 8 \times d$ is 20.0%.

For short pieces we have to consider the influence of the ends, which must show a gradual curve to the test piece proper and must in no way affect the deformation within the gage length.

REDUCTION OF AREA

The reduction of area expresses the percentage change in cross-sectional area at the point of rupture, based on the original cross-sectional area. If f_0 is the original area and f the area at the rupture, then the reduction of area will be $\frac{f_0 - f}{f_0} \times 100\%$.

To determine the cross-sectional area at the rupture the broken surfaces are pressed firmly together and the smallest section is measured. There is still some disagreement as to the value of determining the reduction of area, but it probably gives some hint as to the deformability and the impact toughness.

THE RUPTURE WORK—STRESS-ELONGATION DIAGRAM

The stress deformation diagram or rupture diagram, in which the forces are represented by the ordinates and the elongations by the abscissas, can be drawn, if the elongations of the test specimen corresponding to the respective stresses are carefully measured. Some tensile testing machines have a device which draws the diagram automatically, but usually not very accurately. The work necessary to rupture the specimen is represented in the rupture diagram and can be found by determining the area of the diagram and multiplying it by the scale. If in drawing the diagram the scale for 0.01 in. elongation was 0.1 in. and for 100-lb. load was 0.25 in., then 0.025 sq. in. will represent 1 in.-lb. and 1.0 sq. in. will represent 40 in.-lb. The area of the diagram may be found with a planimeter or by converting the area into a rectangle with the same base and an estimated height, which will produce an equal area. This height is the average rupture force. It is possible to determine the work of rupturing the

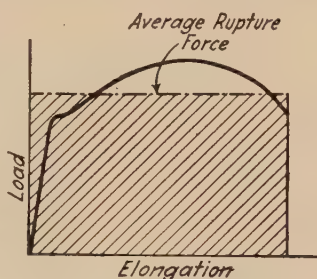


FIG. 4.—Stress-elongation diagram.

specimen quite accurately in this way. Figure 4 shows that for the same average rupture force the work depends only upon the gage length which determines the elongation. Rupture reports therefore must give for comparison the average rupture force and the work for a given gage length. Then it will be possible to calculate the work for any other gage length, for which the elongation has been determined. Sometimes the specific rupture work, which is the work of 1 cu. in. of the deformed volume of the specimen, is determined. This determination of the rupture work is rather difficult and more often the ratio of strength and deformation is used. This ratio is greater than the real rupture work but offers a good figure for judging the material.

THE TEST SPECIMEN

The test specimen must be made to standard specifications, because the results of a test will vary largely according to the

details of form and size, etc. A test piece consists of three parts: the middle part, which is the test piece proper, and the two ends, which serve to fasten the specimen in the heads of the testing machine.

THE AMERICAN STANDARD TEST SPECIMENS¹

Tensile and bend test specimens are to be taken from the rolled or forged material, except in the case of irregularly shaped forgings, where they may be taken from a full size prolongation. Test specimens are not to be annealed or otherwise treated, except as specified in the following paragraph. Bend tests are to be made cold.

Tensile and bend test specimens of material that is to be annealed or otherwise treated before use are, for rolled material, to be cut from a properly annealed or similarly treated short length of the full section of the piece, and for forged material, are to be taken from the treated forgings.

The axis of tensile and bend test specimens taken from rolled bars and forgings, having a uniform cross-section of over $1\frac{1}{2}$ -inch thickness or diameter and from forgings of irregular sections, shall, when practicable, be located at any point midway between the center and outer surfaces of the wall of the original piece when solid, and at any point midway between the inner and outer surfaces of the wall of the original piece if bored. The axis of the test specimen shall also be parallel to the axis of the original piece in the direction in which the metal is most drawn out. Round tensile test specimens shall be machined to the form and dimensions shown in Fig. 5 and the gage length and fillets are to be ground or buffed so that they are free from scratches. The ends of the specimen shall fit the holders of the testing machine in such a way that the load shall be axial. Threaded ends or self-aligning ball ends are recommended.

Bend test specimens shall be $\frac{1}{2}$ in. square in section and not over 6 in. in length, with corners rounded to a radius of not over $\frac{1}{16}$ in.

The axis of tensile test specimens from rolled bars and forgings of uniform cross-section of $1\frac{1}{2}$ in. or under in thickness or diameter shall be machined concentrically from the original piece. Round tensile test specimens may be machined to the dimensions

¹ Society of Automotive Engineers, Handbook 1929, p. 386.

Flat tensile and bend test specimen from plates and rolled shapes shall be of the full thickness of the material as rolled, and the tensile test specimens machined to the form and dimensions shown in Fig. 7. The gage width of test specimen $\frac{1}{4}$ in. or less in

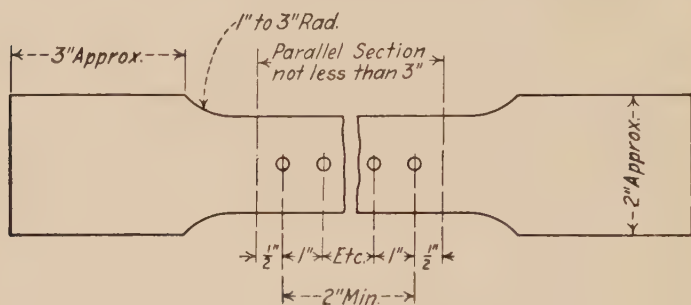


FIG. 7.—Flat tension test specimen.

thickness should be equal to 5 times the thickness, with the exception that in no case is the width to be less than $\frac{3}{4}$ in. The gage length should be 24 times the thickness of the test specimen, but in no case less than 2 in.

THE GERMAN STANDARD TEST SPECIMENS

In order to be sure that the rupture will be within the gage length the piece is turned smaller by 0.0004 to 0.0008 in. over this length. The error that results in the strength will have no influence when the diameter of the specimen is $\frac{3}{8}$ in. and over. But if the piece is to be used for fine measurements of the elastic and proportional limits this undercut is too great. The transition from the heads to the middle part of the piece must be well rounded with fillets. The piece must be held in the machine in such a way that the stress will be well in line with the axis of the specimen. This condition is imperative especially for fine measurements. If the test piece were to suffer an additional bending stress, the whole measurements would be worthless. Test pieces of soft metal may equalize a small eccentricity after the yield point is reached, but brittle material will show too low strength. Figure 8 shows the dimensions for standard specimens for scientific research. The section may be round or flat. For technical

work, test pieces as shown in Fig. 9 are used. To test flat rolled stock, strips and sheet steel test pieces made according to Fig. 10

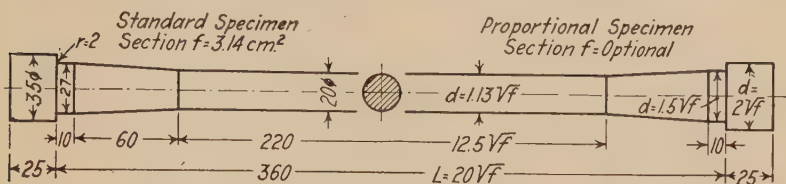


FIG. 8.—Tensile test specimens, German standards.

Dimensions are in millimeters.

are in use. The determining of the reduction is rather difficult, since the area is a square with concave sides. For simplicity the section as shown by the dotted lines in Fig. 11 is used as a basis for calculation.¹

Rupturing the Test Piece.

—The tensile testing machine breaks the test specimen by the movement of the heads of the machine away from each other, the force expended being measured at the same time.

It is essential that the machine

shall work evenly and without jerks. The force is measured by instruments based on the principle of the scales used for

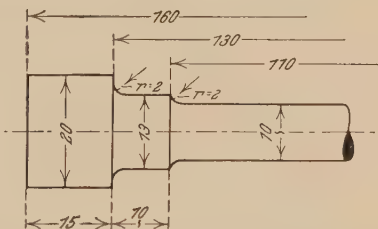


FIG. 9.—German standard tensile test specimen; head detail.

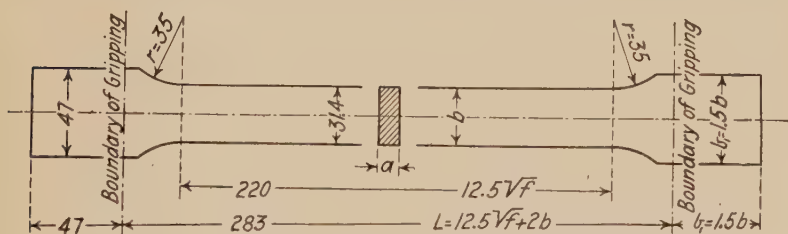


FIG. 10.—Flat test specimen, German standard.

Dimensions are in millimeters.

weighing or the manometer. The tolerance error of the machine is $\pm 1\%$.

¹ W. Kuntze und G. Sachs; *Stahl u. Eisen*, 47 (1927), p. 219.

The Stress in the Test and in Reality.—On account of its simplicity the static rupture test offers the best means of judging the mechanical properties of steel. But it should be remembered that only occasionally is a plain static stress found in actual application. Such a stress would occur in a beam supporting a partition wall provided that the building were free from vibrations. In this case the designer could use the values found in the tensile test for the calculation of the beam. However, nearly all parts



FIG. 11.—Flat test specimen.

Cross-section of rupture.

are subject to sudden loads and vibrations and therefore in calculations for such parts an allowable working stress much less than that determined by the static test must be used. If the value taken for the allowable working stress is too high, there is danger of breakage, whereas if it is too low an unnecessary amount of material will be used. Thus the static rupture test can furnish approximate values only for parts which are subject to dynamic forces.

In order to learn the effect of sudden loads, there have been developed various testing methods, but none of them furnished reliable figures for the designer. Thus the static tensile strength test still retains its place by giving valuable hints as to the allowable stress.

THE SUDDEN LOAD TEST

The desire to learn the effect of sudden loads upon steel led to the development of various test methods. The sudden load test measures the work necessary to rupture the piece, when it is broken suddenly. In this test it is impossible to determine the elastic or proportional limits, the yield point or the breaking point. The only measurements taken are the elongation and reduction of area. The average breaking force may be calculated by dividing the work expended by the elongation. It is customary to refer the work expended to the unit volume of the piece. This test does not furnish basic figures for the designer, but does show the effect of sudden loads. Although this test is simple in procedure and in preparation of the specimens and although the results are of considerable general value, it has not yet found wide use.

The sudden load test is best made in an impact machine (see

page 17). One end of the test piece is fastened to the rear end of the hammer of the machine, and the other end, which has a cross-head, strikes against the anvil breaking the piece. The piece may be bolted to the hammer in testing tough material but for other work a spherical bearing is necessary to insure that the line of stress shall correspond to the axis of the piece.

The work used in breaking the piece is measured just as in the ordinary impact test. According to experiments by F. Körber and R. F. Sack,¹ the length of the test piece should not be greater than 5 times the diameter, otherwise two reductions may occur. Figure 12 shows the dimensions of the piece. Since the work is referred to a certain volume, it will be necessary to mark this volume exactly on the piece by its dimensions.

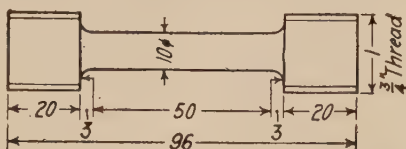


FIG. 12.—Sudden-rupture test specimen.
Dimensions are in millimeters.

Calculation of Rupture Force and Rupture Work.—Rupture elongation and reduction of area are determined just as in the case of the static tensile test. To find the average rupture force and the specific rupture work for 1 cu. in. of the volume deformed, this entire work is scaled so that the work exerted at foundation of the machine, at the heads, and so on is neglected. This error is hard to determine, but will have little effect on the results. By dividing the work done by the elongation, the average rupture force is obtained; dividing the work expended by the volume of the cylindrical part of the piece between the shoulders gives the specific rupture work.

THE IMPACT TEST

The impact or notch strike test, or better, notch bending test, is a very important means of showing the notch effect at sudden load. The test is made by breaking a notched specimen in a pendulum machine, the work required being measured. One of the commonly used machines is the Charpy pendulum tester. In this type of machine the hammer strikes the specimen on the side opposite the notch and midway between the supports, and

¹ Mitteilungen aus dem Kaiser-Wilhelms-Institut für Eisenforschung, II. Band.

after breaking the piece continuous on its upward swing. The energy used up in breaking the specimen is the product of the weight of the pendulum and the difference between its height of fall and height of rise. Figure 13 shows a schematic view of the machine.

Calculation of Height of Fall and Rise.—The machines are equipped with devices to measure the various heights of the pendulum accurately. Figure 14 shows a pendulum machine. The machine does not record the height directly, but rather the angle

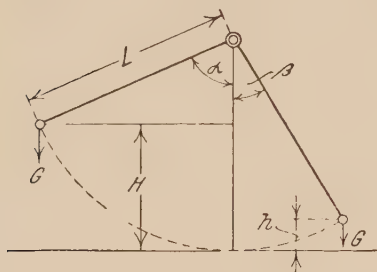


FIG. 13.—Impact pendulum.

formed by a line connecting the center of gravity of the hammer and the pendulum axis with the vertical. Since the distance of the hammer from the fulcrum is known, the height is easy to calculate. If L is the actual pendulum length, G the weight of the hammer, and α and β are the two scaled angles, then the heights H and h will be $H = L - L \cos \alpha$, $h = L - L \cos \beta$. The energy used for breaking the piece:

$$\begin{aligned} HG - hG &= G(L - L \cos \alpha) - G(L - L \cos \beta) \\ &= G(\cos \beta - \cos \alpha)L. \end{aligned}$$

G and L are given on the gage table of the machine, α and β are found during the test.

The Test Specimen.—Although the stress in the impact test is decidedly a bending stress, it is customary to refer the work used to the initial area of the original section. Figure 15 shows the dimensions of a German standard test piece for the notch breaking test. The section of the piece is 30×30 mm. (1.18×1.18 in.).

Before starting the test it is necessary to make sure that the test piece lies properly on the anvil and that the hammer is just opposite the notch. As already mentioned the work used in breaking the piece is referred to the unit area and is called the notch toughness or specific impact work. To obtain results that may be readily compared with each other, it is necessary to use

the standard test pieces, since the law of similarity does not hold true for proportional test pieces.

The Working Constant and Working Velocity.—The work of M. Moser¹ leads to an entirely new interpretation of the impact

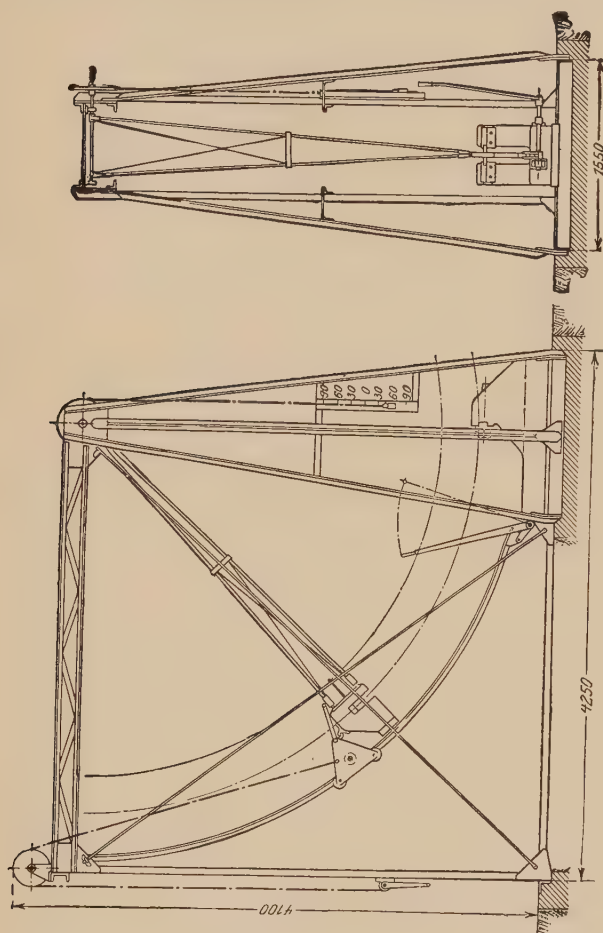


FIG. 14.—Pendulum impact tester.

test. On examination of the broken test piece it can be seen that only a part of the volume of the test piece has been deformed. If the work used for breakage is referred to this deformed volume, the working constant (foot-pounds per cubic inch), which is inde-

¹ *Stahl u. Eisen*, 43 (1923), p. 935.

pendent of the form of the test piece, is obtained. The work used up therefore consists of the product of the working constant and the deformed volume. The theoretical maximum of this deformed volume is given by the dimensions of the piece, whereas the actual deformed volume depends upon the impact speed and upon the material. The speed with which materials can change their form and thus store energy, varies, so that we may distinguish easily deformable and difficultly deformable materials. The percentage part, which the deformed volume is of the maximum volume, is, according to Moser, a measure of speed of deformability.

Moser thus distinguishes two important properties: the working constant, that is, the work necessary for the deformation

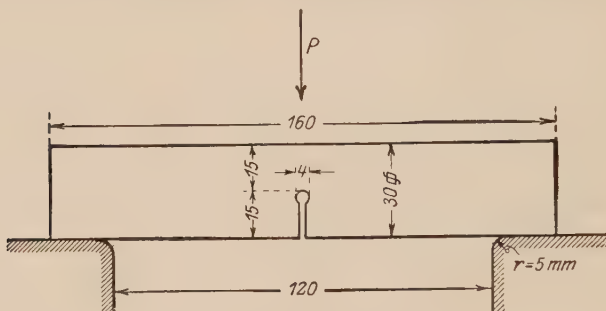


FIG. 15.—Notch-breaking test.

Dimensions are in millimeters.

of 1 cu. in.; and the working speed, that is, the speed with which the material can change its form. It is obvious that it is important to be able to find close values for these properties. For parts which are subject to static stresses, boiler plates, for example, a high working constant is required, whereas for dynamically stressed parts of machines, such as crankshafts and axles, a high working speed is needed also.

In order to determine both these properties, two specimens are needed: one, with a rupture section 1.18×0.591 in., maximum working volume 0.763 cu. in.; and another one of half width with a rupture section 0.591×0.591 in., maximum working volume 0.384 cu. in. Both pieces are tested and the work required is calculated. For example, we have found a work of 296 ft.-lb. on breaking the small piece. The working constant then is found by dividing the work by the maximum volume $296/0.384 =$

770 ft.-lb. per cu. in. The large test piece may have used up 498 ft.-lb. Its working volume we can find by dividing the work by the working constant $498/770 = 0.647$ cu. in. The work speed then is $\frac{0.647}{0.763} 100 = 85\%$. The tested material thus has a working constant 770 ft.-lb. per cu. in. and a working speed of 85%, which is a medium working constant and a high working speed. According to Moser's tests the working constant may be as high as 1775 ft.-lb. per cu. in. and the working speed as much as only a few per cent less than 100%.

In the impact test the examination of the structure of the broken piece is very important. Tough material shows a fibrous structure on the contour, but long experience is necessary to make proper deductions as to the properties of the material from the appearance of the break.

Careful experimental work on the law of similarity as applied to the impact test has been done by R. Mailänder,¹ who also determined the relation between temperature, toughness and the volume of the test specimen.²

Notch Test and Tensile Strength.—Although the impact test does not give the designer definite values for use in calculations, yet it is of extreme importance, since it gives an excellent indication of the quality and makes it possible to detect wrong heat treatment. It is not always possible in design to avoid sudden changes in section and in such cases it is important to know if the material possesses strength in notched sections. An attempt has been made to find the relations, if any, between notch toughness and the results of static tests. There are certain similarities between the reduction of area and the working constant, but as yet it is not possible to eliminate the impact test by use of the reduction of area values.

THE FATIGUE TEST

The Krupp Fatigue Testing Machine.—It has been known for some time that loads far below the breaking strength of a material may cause failure if applied a very large number of times, and this has led to the development of a machine to test specimens

¹ *Stahl u. Eisen*, 46 (1926), p. 1752.

² E. Maurer and R. Mailänder, *Stahl u. Eisen*, 45 (1925), p. 409.

under such conditions. In Germany the fatigue-testing machine of Krupp is almost universally used for this purpose (Fig. 16). The dimensions of the test piece are given in Fig. 17. Some pieces have round notches, whereas others have very sharp notches.

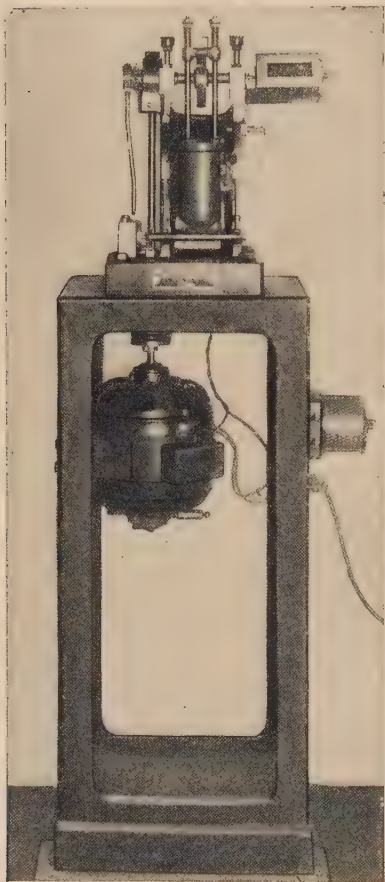


FIG. 16.—Krupp fatigue tester.

For exact tests the round notch specimens are used and these notches must be made very carefully since even slight scratches from machining may start a break. The apparatus consists of a small drop hammer 4 kg. = 8.8 lb. in weight, which is lifted about 1 in. at regular intervals and then drops down on the piece. The machine is driven by an electric motor at a speed of from 60 to 120 strokes per minute. The number of strokes is registered by a counter, which is automatically stopped at breakage. During the test the piece is turned so that either 2 or 25 strokes occur during one revolution. When the piece is turned so that 2 strokes occur during one revolution, the neutral axis of the bar does not change its position and a fracture like that shown in Fig. 18a is produced. On the other hand, if the piece is turned through an angle less than 180 deg. after each stroke, then each

fiber will undergo a change of stress from a maximum to zero and then to the opposite maximum. This produces a fracture such as is shown in Fig. 18b.

Characteristics of Fatigue Breaks.—The appearance of fatigue fractures may be explained by considering the manner of their

formation. The alternating stress first causes a tiny crack to appear in the outer fibers of the piece. This crack then spreads toward the interior of the bar, the faces of the partial fracture

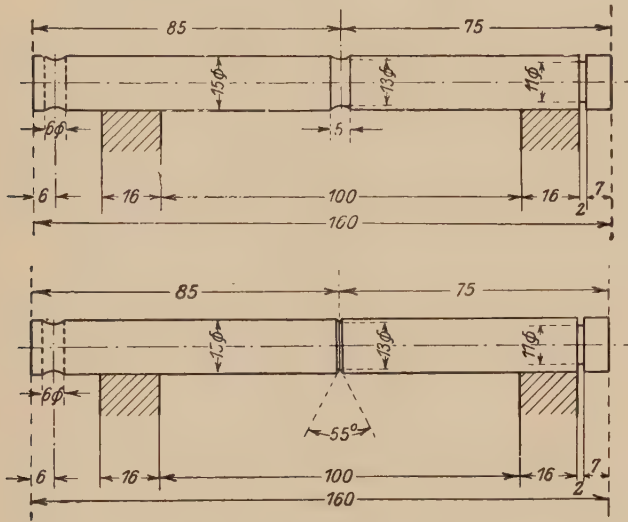


FIG. 17.—Fatigue test specimen.

Dimensions are in millimeters.

being smoothed by rubbing against each other under the influence of the alternating load. Then when the crack has proceeded so far that the remainder of the bar can no longer stand the stress,

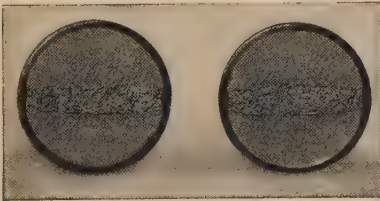


FIG. 18a.

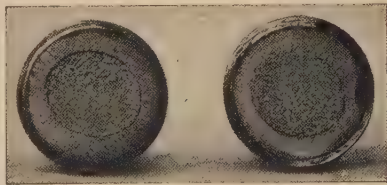


FIG. 18b.

FIG. 18.—Fatigue fractures.

the piece suddenly breaks. This part of the bar which breaks suddenly has a granular fracture like bars broken in a tensile testing machine, so that a fatigue fracture consists of a granular

core surrounded by a comparatively smooth rim. Fatigue breaks are characterized by the lack of any preceding deformation.

Fatigue Test and Yield Point.—The fatigue test, like the impact test, does not furnish values that can be used directly in design, but does give a means of comparing different materials. It has been found that the number of strokes necessary to break a bar bears some relation to its yield point. This might be expected, since a high yield point is accompanied by a high elastic limit, which would increase the resistance of the outer fibers to fatigue effects. Fatigue values obtained with different types of testing machines are not readily comparable.

The fatigue test is not extensively used at present in spite of the information which it gives regarding the relative ability of material to withstand alternating stresses.

References on other methods of fatigue testing are given in a list compiled by R. Mailänder.¹

THE HARDNESS TEST

The Brinell Test.—In the following text hardness shall be regarded as the resistance which a material offers to the penetration of another harder material. The instrument most commonly used for measuring hardness is the Brinell tester. The test consists of pressing a ball of a certain diameter into the piece being tested, until a small impression is made. The hardness is determined from the load used, the diameter of the ball, and the diameter of the impression. Figure 19 shows diagrammatically how the test is made.

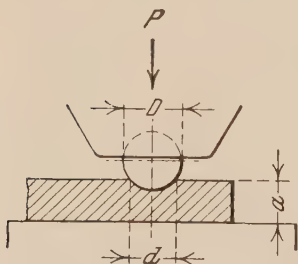


FIG. 19.—German standard DIN 1605 Brinell test.

D = diameter of ball, in millimeters;
 P = load, in kilograms;
 d = diameter of impression, in millimeters.

Pieces to be tested by this method must be machined or ground, so that the surface is smooth.

The pressure, which is furnished by an oil pump, can be regulated by the accumulator and is measured by a manometer or gage. In making a test the maximum pressure should be attained

¹ *Stahl u. Eisen*, 44 (1924), pp. 585, 624, 657, 684, 719.

within fifteen seconds and should continue for thirty more seconds, except when hard steel is being tested, in which case ten seconds at maximum load is sufficient. The loads to be used with pieces of various thicknesses are shown in the following table:

Thickness of Testpiece, a , mm. .	Diameter of the Ball, D , mm.	Load for Cast Iron and Steel, Kg.
Over 6.....	10	3000
From 6 to 3.....	5	750
Below 3.....	2.5	187.5

The diameter of the impression is measured with a microscope, to hundredths of a millimeter. If the impression is oval, the average of the two diameters is used. Two tests are usually made and the average taken.

Calculation of Brinell Hardness Number.—The hardness number is calculated by the formula:

$$H = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})},$$

in which P is the load exerted on the ball in kilograms;

D is the diameter of the ball in millimeters;

d is the diameter of the impression in millimeters.

To denote the conditions of the test briefly, an abbreviated expression is used; for example, for $D = 5$ mm., $P = 750$ kg., and thirty seconds continuation of load: $H\ 5/750/30$. For the standard test the abbreviation H_n is used. Thus H_n stands for $H\ 10/3000/30$.

The hardness of the balls is determined by pressing two balls together with a certain load P . The average pressure exerted on the contact area is the ball hardness. For good balls it must be at least 630 kg. per mm.²

Hardness measurements must of course be made far enough from the edge of the piece that no deformation of the edge occurs, otherwise the values obtained will not be correct.

To obtain correct hardness values with the Brinell machine it is necessary that the material shall have the same hardness for

some distance from the surface as at the surface. Tests made on a thin carburized layer will be of little value, since the penetration will be influenced by the lower resistance of the softer core. Likewise the result will not be accurate when the hardness of the material being tested is nearly as great as that of the ball.

Brinell Hardness and Tensile Strength.—Brinell hardness is similar to tensile strength in that the force is referred to a certain area. A relation between these two properties for two different materials has been found as follows:

For carbon steel	30-100 Kg. per mm. ²	
	(42 000-140 000 lb. per sq. in.)	Strength = 0.36 <i>H</i>
For chrome-nickel steel	65-100 Kg. per mm. ²	
	(92 000-140 000 lb. per sq. in.)	Strength = 0.34 <i>H</i>

It is this relation which makes the hardness test so valuable, since it becomes possible to determine the tensile strength of a material without making special test pieces. The hardness test also makes it possible in some cases to test nearly all parts of a machine or to determine if a certain part is uniform throughout. Thus it is common practice to make Brinell tests on the ends and centers of annealed bars to see if the heat treatment was uniform. This is especially important in the case of complicated drop forgings. Best results are obtained if tests are made on the cross-sections of the piece, but this is usually too difficult and the test are made on surfaces.

Table II gives the Brinell numbers corresponding to different diameters of the impression when a certain maximum load and diameter of ball are used.¹ In Table III, which is widely used in the German industry, the tensile strength corresponding to different diameters of impression is given. However, these values do not check the conversion factor given previously.

Other Tests, Strike Tests.—The size of the Brinell machine limits the size of pieces that may be tested. In order to test larger parts several methods have been developed, the so-called strike test methods. In certain of these methods, a spring or falling weight presses the ball into the material. Others press a ball by means of a hammer into the material being tested and at the same time into another material, whose Brinell hardness is known.

¹ Otto Wawrziniok, Handbuch des Materialprüfungswesens, p. 203.

The ratio of the dimensions of the two impressions gives a basis for calculating the hardness of the piece being tested.

The Method of Herbert.—A new development in hardness testing is the Herbert pendulum instrument. This device is supported on a ball, which is placed on the material to be tested. The ball acts as the pivot about which the pendulum swings and the number of vibrations depends on the depth to which the ball penetrates into the material.

The Scleroscope.—Another hardness testing device is the scleroscope, which was invented by A. F. Shore. This instrument, which is shown in Fig. 20, is particularly adapted to testing large parts. A small hammer with a diamond point drops down a glass tube onto the test piece and the height of rebound of the hammer, read on a scale attached to the tube, is taken as a measure of the hardness.

The glass tube must be perpendicular, when making a test. This method is suitable for testing hard materials only, and for such materials is an important supplement to the Brinell hardness. Only within certain limits is it possible to find a relation between scleroscope hardness and Brinell hardness, and between scleroscope hardness and other physical properties.

The Scratch Method.—For completeness, the scratch method of Martens, which is seldom used, should be mentioned. In this

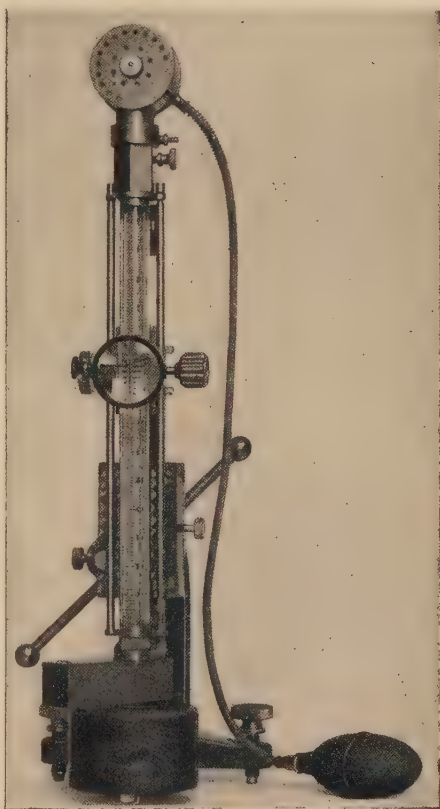


FIG. 20.—Shore's scleroscope.

method the load necessary to produce a scratch of a certain width with a diamond point, is measured.

Technical tests are sometimes used for purchasing inspection, as:

The Bending Test.—To test the cold bending properties of a material, flat rolled pieces of $1\frac{1}{2}$ to 2 in., with rounded edges, if not otherwise specified, are slowly bent around a mandrel of a

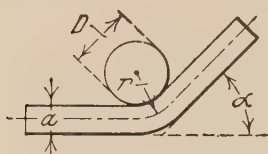


FIG. 21.—German standard DIN 1605 bending test.

certain radius until a prescribed angle is reached (Fig. 21). Another method is first to bend the pieces around a mandrel and then bend the ends together in a vise. In the first case, the piece should not show fissures after completing the test. In the second method the

bending value, as developed by Tetmayr, must reach a specified value. When a piece is bent around a mandrel, the bending values for the various diameters are:

D	0	$0.5a$	$1.0a$	$1.5a$	$2.0a$	$2.5a$	$3.0a$
B_g	100	67	50	40	33	28	25

In these values D is the diameter of the mandrel, B_g is bending value, and a is thickness of test piece in millimeters.

The Forging Test.—For testing the forging qualities, the bend test is made at a red heat. The test is more severe, if the piece is notched on the side away from the mandrel. The flattening test, in which the metal is forged into a thin sheet, may also be used. In this test the edges of the sheet should not show fissures. The so-called mandrel test, in which the metal is heated red-hot and pierced with a mandrel, is used occasionally.

The Welding Test.¹—The weldability may be determined by welding the test piece with the ends slightly overlapped. They must not then separate, when bent hot or cold. The tensile strength of the unwelded piece should be at least a given fraction of that of the unwelded portions.

The Multiple-bending Test.²—Wire and sometimes sheet-metal strips are tested by clamping them in an ordinary vise and breaking them by repeated bending forward and backward

¹ DIN, 1605.

² Otto Wawrziniok, Handbuch des Materialprüfungswesens, p. 226.

through 180 deg. A complete bend involves moving the piece twice through 180 deg. or back to the initial position. The bend values depend upon the thickness of the piece and the radius of the vise jaws, which should always be given in the report. Usually wire from $\frac{3}{16}$ in. upward is tested in jaws with a radius of $\frac{3}{8}$ in. and small wire in jaws of $\frac{3}{16}$ -in. radius.

The Torsion Test.¹—The torsion test is very efficient in testing the quality of wire. The wire is fastened in two jigs and twisted, the number of twists being recorded by a counting device. The gage length of the test piece is 75 times the diameter, and at least 6 in.

The Ductility Test.—The ductility test is used for testing sheet metal for which the ability to be drawn, pressed, or folded is important. The Erichsen machine is largely used for making these tests. Circular pieces of metal are clamped around the circumference in a fixture and then the center of the piece is pressed to a certain depth. Sometimes the force necessary to do this is measured. The depth obtained before a piece of a given material breaks depends upon the thickness. Figure 22 gives a chart, showing the depth to which various gages of materials must withstand pressing before breaking.

¹ Otto Wawrziniok, *Handbuch des Materialprüfungswesens*, p. 227.

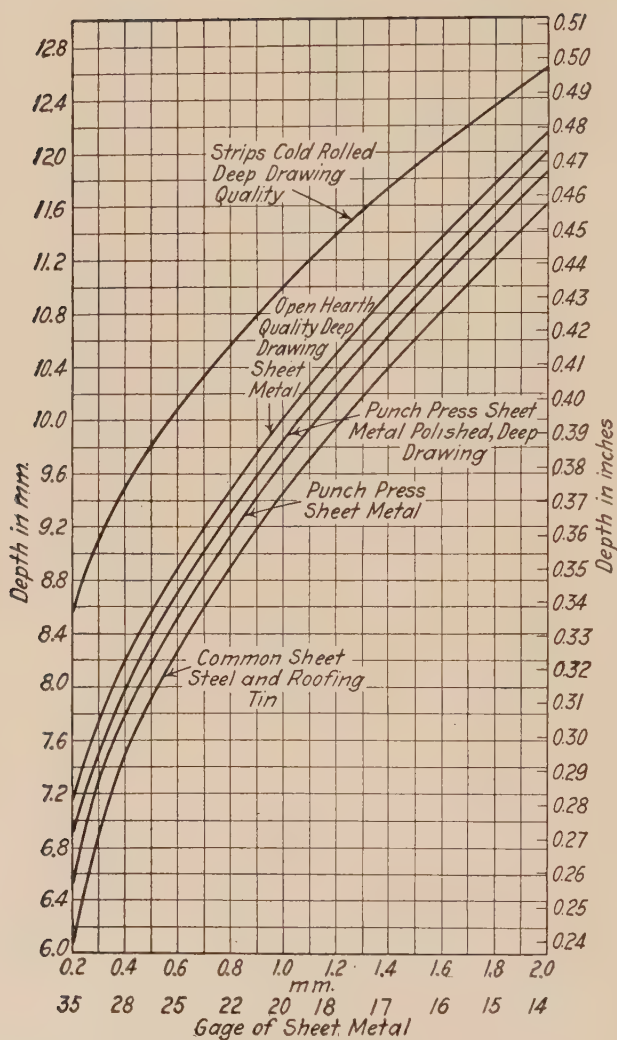


FIG. 22.—Erichsen chart for various kinds of steel.

Courtesy of A. M. Erichsen, Berlin, Germany.

TABLE II.—DIAMETER OF IMPRESSION AND HARDNESS NUMBER, AFTER
BRINELL, FOR 10-mm. BALL AND 3000-Kg. LOAD

Diameter of Impression, mm.	Hardness Number, Load 3000 Kg.	Diameter of Impression, mm.	Hardness Number, Load 3000 Kg.
2.00	946	4.50	179
2.05	898	4.55	174
2.10	857	4.60	170
2.15	817	4.65	166
2.20	782	4.70	163
2.25	744	4.75	159
2.30	713	4.80	156
2.35	683	4.85	153
2.40	652	4.90	149
2.45	627	4.95	146
2.50	600	5.00	143
2.55	578	5.05	140
2.60	555	5.10	137
2.65	532	5.15	124
2.70	512	5.20	131
2.75	495	5.25	128
2.80	477	5.30	126
2.85	460	5.35	124
2.90	444	5.40	121
2.95	430	5.45	118
3.00	418	5.50	116
3.05	402	5.55	114
3.10	387	5.60	112
3.15	375	5.65	109
3.20	364	5.70	107
3.25	351	5.75	105
3.30	340	5.80	103
3.35	332	5.85	101
3.40	321	5.90	99
3.45	311	5.95	97
3.50	302	6.00	95
3.55	293	6.05	94
3.60	286	6.10	92
3.65	277	6.15	90
3.70	269	6.20	89
3.75	262	6.25	87
3.80	255	6.30	86
3.85	248	6.35	84
3.90	241	6.40	82
3.95	235	6.45	81
4.00	228	6.50	80
4.05	223	6.55	79
4.10	217	6.60	77
4.15	212	6.65	76
4.20	207	6.70	74
4.25	202	6.75	73
4.30	196	6.80	71.5
4.35	192	6.85	70
4.40	187	6.90	69
4.45	183	6.95	68

TABLE III.—DIAMETER OF IMPRESSION AND STRENGTH IN Kg. PER mm.² AND LB. PER SQ. IN., AFTER BRINELL, FOR 10-MM. BALL AND 3000-Kg. LOAD

Diameter of Impression, mm.	Strength		Diameter of Impression, mm.	Strength	
	Kg. per mm. ²	1000 Lb. per Sq. In.		Kg. per mm. ²	1000 Lb. per Sq. In.
2.50	207	294	4.55	63	89.5
2.55	199	283	4.60	61.8	88
2.60	191	272	4.65	60.5	86
2.65	184	262	4.70	59	84
2.70	177	252	4.75	57	81
2.75	170	242	4.80	56	79.5
2.80	164	233	4.85	55	78.2
2.85	159	226	4.90	53	75.5
2.90	153	218	4.95	52	74
2.95	148	211	5.00	51	72.5
3.00	143	204	5.05	50	71
3.05	138	197	5.10	49	69.7
3.10	133	189	5.15	48	68.2
3.15	129	184	5.20	47	66.9
3.20	125	178	5.25	46	65.5
3.25	121	172	5.30	45	64
3.30	117	167	5.35	44	62.5
3.35	114	161.5	5.40	43	61.2
3.40	110	156.5	5.45	42	59.8
3.45	107	152	5.50	42	59.8
3.50	104	148	5.55	41	58.4
3.55	101	144	5.60	40	57
3.60	98	139	5.65	39	55.5
3.65	95	135	5.70	38	54
3.70	92	131	5.75	38	54
3.75	90	128	5.80	37	52.7
3.80	87	124	5.85	36	51.5
3.85	85	121	5.90	35	49.8
3.90	82.9	118	5.95	35	49.8
3.95	80.8	115	6.00	34	48.4
4.00	78.8	112	6.05	33	47
4.05	76.7	109.5	6.10	33	47
4.10	74.6	106.5	6.15	32	45.5
4.15	72.9	104	6.20	32	45.5
4.20	71.2	101.5	6.25	31	44.1
4.25	69	98	6.30	31	44.1
4.30	67.8	96.5	6.35	30	42.7
4.35	66	94	6.40	29	41.3
4.40	64	91	6.45	29	41.3
4.45	63	89.5	6.50	28	39.8
4.50	63	89.5			

CHAPTER II

METALLOGRAPHY

Forms of Carbon in Iron.—The most important alloying element in steel and cast iron is carbon. Comparatively small amounts of this element may have a considerable effect on the properties of the metal. Carbon may exist in iron-carbon alloys as graphite, as a form of free carbon, or as a carbide of iron called cementite. In gray cast iron, considerable of the carbon exists in the form of flat crystals of graphite which gives to the fracture of this iron its characteristic gray or black color. White cast iron and steel, on the other hand, contain carbon entirely in the form of cementite and have a grayish white fracture.

Solidification.—The addition of carbon to iron reduces the melting point of the metal. Thus white pure iron completely melts and solidifies at 1527°C . (2780°F .); iron containing 1.7% carbon begins to solidify at about 1375°C . (2507°F .), and becomes completely solid while at 1145°C . (2093°F .).

Cooling and Crystallization.—When such an alloy in the molten state is cooled to the point at which solidification begins, small solid particles begin to separate out. These small particles serve as centers of crystallization around which other particles solidify in crystalline forms. As the growth of these crystals continues, they begin to interfere with each other so that the metal, when finally entirely solid, is composed of irregularly shaped grains.

Austenite.—In iron-carbon alloys, containing up to 1.7% carbon, the metal solidifies entirely in the form of crystals of a solid solution of carbon in iron, called austenite. The appearance of this constituent is shown in Fig. 23,¹ the twinned crystals being quite characteristic.² Iron at the temperature of final

¹ On the preparing and the judging of polished sections see E. Pruess, G. Berndt und M. v. Schwarz, Berlin, 1927, *Eisenprüfung durch Ätzung*.

² Plastic Deformation of Crystals, see M. v. Schwarz, *Metallphysik*, Leipzig, 1925, p. 5.

solidification cannot dissolve more than 1.7% carbon and when a melt containing more than this amount solidifies, crystals of austenite separate out until the temperature reaches 1145° C. (2093° F.), at which point the rest of the alloy solidifies as a fine granular mixture.

The Eutectic of Iron-carbon Alloy—Ledeburite.—This mixture, which consists of austenite and the excess carbon in the form of iron carbide, has an average composition of 4.2% carbon at the temperature of solidification. Such a fine mixture



FIG. 23.—Austenite, $\times 250$.

solidifying at constant temperature is known as a eutectic and the eutectic in the iron-carbon system has been given the special name ledeburite. The structure of this constituent is shown in Fig. 24. Ledeburite is a characteristic constituent in pig iron. Since at temperatures above about 721° C. (1330° F.) iron-carbon alloys of 1.7% carbon consist of crystals of solid solution only and these containing 4.2% carbon consist entirely of ledeburite, it is evident that such alloys containing 1.7 to 4.2% carbon will consist of mixtures of these two constituents. The amount of ledeburite increases as the carbon increases. In Fig. 25, which shows the structure of an iron-carbon alloy, contain-



FIG. 24.—Ledeburite, $\times 100$.



FIG. 25.—Under-eutectic white pig iron, $\times 100$.

ing 3.4% carbon, the solid solution crystals, which were the first to solidify, are shown in a ground mass of eutectic.

PRODUCTS OF DECOMPOSITION OF AUSTENITE ON SLOW COOLING

Secondary Cementite.—Iron-carbon alloys, in being cooled below the solidification temperature, undergo further transformation at certain temperatures, which vary with change in carbon content. In the first place, the solubility of carbon in iron decreases with decreasing temperature until at 721° C. (1330° F.)

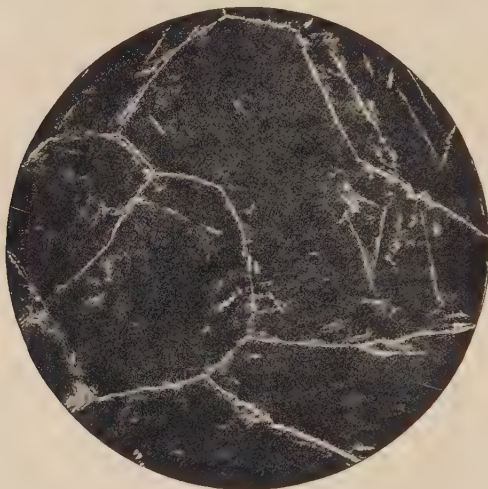


FIG. 26.—Pearlite and secondary cementite, $\times 100$.

only about 0.9% carbon can be contained in solution. The excess carbon separates on cooling in the form of needles of iron carbide between the grains of austenite. This cementite or iron-carbide is called secondary cementite, to distinguish it from the primary cementite which separates directly from the liquid solution. Figure 26 shows cementite needles in an alloy of 1.4% carbon.

The Eutectoid Pearlite: Ferrite, Iron Carbide.—Another change which takes place in iron-carbon alloys in the solid state is a transformation of the iron into a different crystalline form called ferrite or α -iron, which is magnetic, whereas austenite is

non-magnetic. This change begins at various temperatures depending on the carbon content and is completed at about 720°C. (1328°F.). When the carbon content is about 0.9%, this change takes place completely at a constant temperature of around 720°C. , and as the carbon content decreases the temperature at which the transformation starts increases. Carbon is practically insoluble in α -iron, so that in iron-carbon alloys below 720°C. (1328°F.) the carbon all exists as iron carbide or as free carbon. The situation on cooling through the transforma-



FIG. 27.—Pearlite, $\times 100$.

tion zone is similar to that of the solidifying metal, when the carbon content is less than 0.9%. Pure iron or ferrite separates when the beginning of the transformation zone is reached and the remaining solid solution becomes richer in dissolved carbon. When the carbon content of the solid solution reaches 0.9%, which occurs at 720°C. (1328°F.), it changes completely to an aggregate of ferrite and iron carbide. Such an aggregate of definite composition separating at constant temperature from solid solution is called a eutectoid. The eutectoid of iron and cementite contains 0.9% carbon and is known as pearlite. The structure of pearlite is shown in Fig. 27, the lamellar appearance

is due to the occurrence of the cementite in plates which appear as needles in the picture. No other transformations occur in iron-carbon alloys below 720°C . (1328°F .) when they are slowly cooled.

The Iron-Carbon Diagram.—The various transformations that have been considered are represented by the diagram given in Fig. 28. This diagram will now be explained by considering the

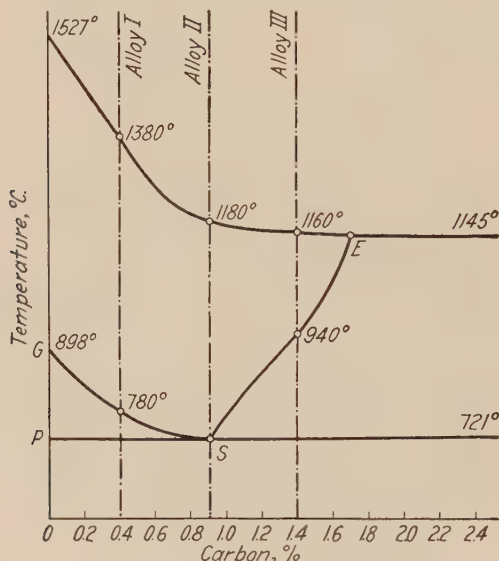


FIG. 28.—Iron-carbon diagram.

changes which take place on cooling iron-carbon alloys of the carbon contents indicated on the diagram.

Alloy I, which contains 0.4% carbon, becomes completely solid on passing 1380°C . (2516°F .) and then consists of crystals of homogeneous solid solution or austenite. On further cooling, the crystals remain unchanged until a temperature of 780°C . (1436°F .) is reached. At this point free ferrite begins to form, while the austenite increases in carbon content. As the temperature drops, the composition of the remaining austenite follows the line GS and ferrite continues to form. At 720°C . (1328°F .) the remaining austenite has a carbon content of 0.9% and is completely changed to pearlite. Figure 29 shows ferrite (white)

and pearlite (dark) as they would be found in such a steel when slowly cooled.

Alloy II with 0.9% carbon finished solidifying at 1180° C. (2156° F.), forming crystals of austenite. There is no further change on cooling until 720° C. (1328° F.) is reached, at which point the austenite is completely converted to pearlite. Figure 27 shows the microstructure of a sample consisting of pearlite only.

Alloy III containing 1.4% carbon finishes solidifying at 1160° C. (2120° F.), at which temperature it is composed com-

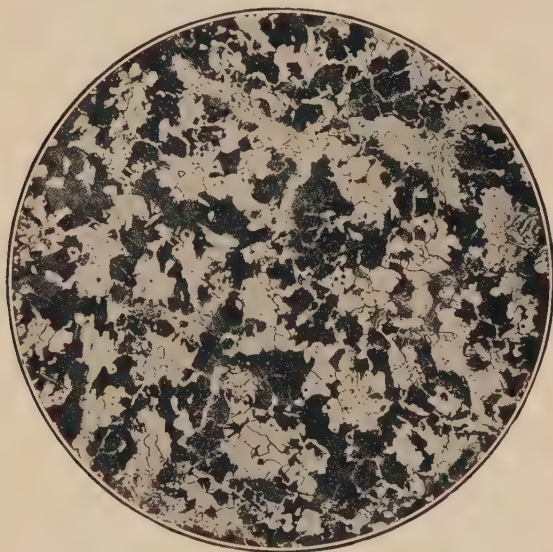


FIG. 29.—Ferrite and pearlite, $\times 100$.

pletely of austenite. At 940° C. (1724° F.) these solid solution crystals begin to separate out cementite, the composition of the remaining austenite following line *ES*. At 720° C. (1328° F.) the remaining austenite reaches a composition of 0.9% and changes completely to pearlite. Figure 26 shows the type of structure that would be obtained in such a case, the pearlite appearing dark and the cementite light in the picture.

The slowly cooled alloy I consists at room temperature of ferrite crystals and pearlite, as shown on Fig. 29. At 720° C. (1328° F.), on heating, the pearlite changes into crystals of solid solution or austenite containing 0.9% carbon. As heating is

continued, the ferrite dissolves in the austenite with a decrease in the carbon content of the latter. At 780°C . (1436°F .) the ferrite is completely dissolved and the austenite contains 0.4% carbon. No other change takes place until the austenite begins to melt at 1160°C . (2120°F .).

Alloy III consists of cementite needles and pearlite at room temperature. At 720°C . (1328°F .) the pearlite changes to austenite of 0.9% carbon content. As the temperature rises the austenite dissolves the cementite with increase in carbon content, until at 940°C . (1724°F .) the cementite is completely dissolved and the austenite contains 1.4% carbon. Above 940°C . the alloy consists entirely of austenite and no change occurs until the metal begins to melt at 1160°C . (2120°F .).

The temperatures given in the diagram of Fig. 28 are those corresponding to equilibrium conditions. As a consequence of the inertia, the temperature of the changes obtained in actual cooling and heating of the alloys would not be the same. In cooling, the amount of undercooling depends on the rate of cooling and the temperature from which it was started.

PRODUCTS OF DECOMPOSITION OF AUSTENITE ON FAST COOLING

The various changes that have just been discussed take place as stated only when the steel is very slowly cooled, and some of them may be altered or prevented by rapid cooling. However, the tendency for austenite to decompose is so great that in the case of the pure iron-carbon alloys it cannot be retained at room temperature, even by the most rapid cooling. However, the decomposition products of austenite under such conditions may have an entirely different appearance from that of pearlite. Very rapid cooling produces martensite, which may be recognized by its needle structure (Fig. 30). By slower cooling troostite is produced. Troostite occurs as dark knots and is easily recognized in etching by its fast darkening. Figure 31 shows dark patches of troostite with martensite. Still slower cooling gives sorbite (Fig. 32) which is the last decomposition product before pearlite. The structure of sorbite is so fine that it cannot be resolved with even very high power microscopes. Since sorbite is the last decomposition product before pearlite and often occurs with the



FIG. 30.—Martensite, $\times 250$.

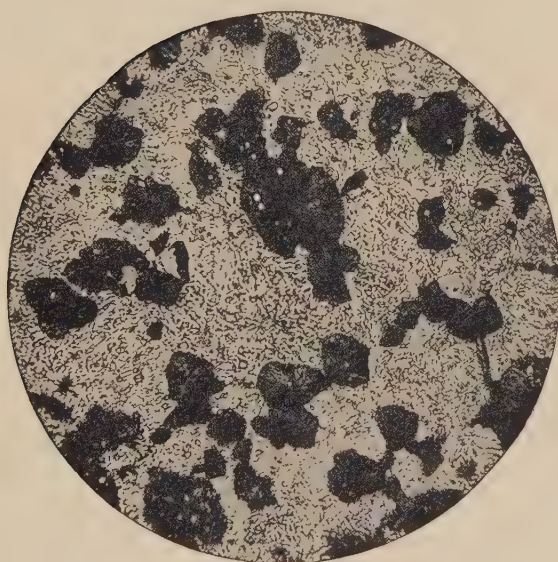


FIG. 31.—Troostite and martensite, $\times 300$.

latter, it may be concluded that sorbite is merely pearlite in which rapid cooling has caused the ferrite and cementite plates to be too fine to be visible through a microscope.

The decomposition products of austenite which are obtained by rapid cooling may be transformed by reheating. On reheating, martensite is changed to troosite and then to sorbite.

Granular Pearlite.—If the quenched steel is heated long enough at a sufficiently high temperature, pearlite will be formed.

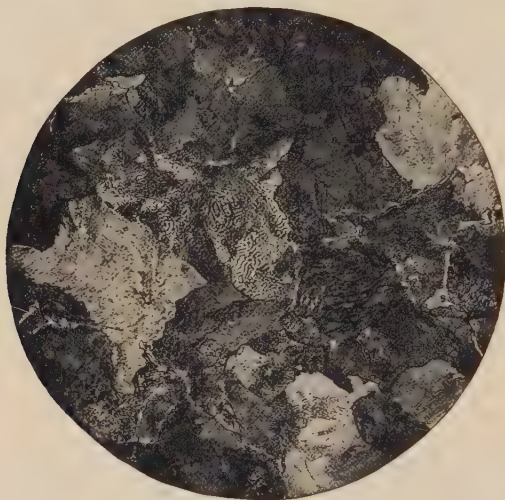


FIG. 32.—Sorbite and fine lamellar pearlite, $\times 300$.

Pearlite formed in this way contains the cementite in the form of granules and is called granular pearlite (Fig. 33) to distinguish it from the lamellar form which is obtained on slow cooling.

Austenitic Steels.—Austenite is transformed on quenching ordinary steels, but if a sufficient amount of certain alloying elements such as manganese or nickel is present, austenite may be retained at room temperature. Such austenite steels are soft and tough, have a medium tensile strength and low yield point, and work with difficulty when cold.

Martensite.—Ordinary steels when very rapidly cooled contain martensite as constituent. This constituent is very hard and tends to make the steel hard and brittle but gives it a high tensile strength. The elongation and reduction of area of martensitic steels are very small.

Troostite.—When steels containing martensite are annealed the martensite changes to troostite, which is softer. As more and more of the martensite is changed to troostite on annealing, the hardness, brittleness and tensile strength of the steel decrease, but the elongation and reduction of area increase.

Sorbite.—As the annealing temperature is increased the troostite changes to sorbite, which is an aggregate so fine-grained that the particles cannot be distinguished under a microscope.

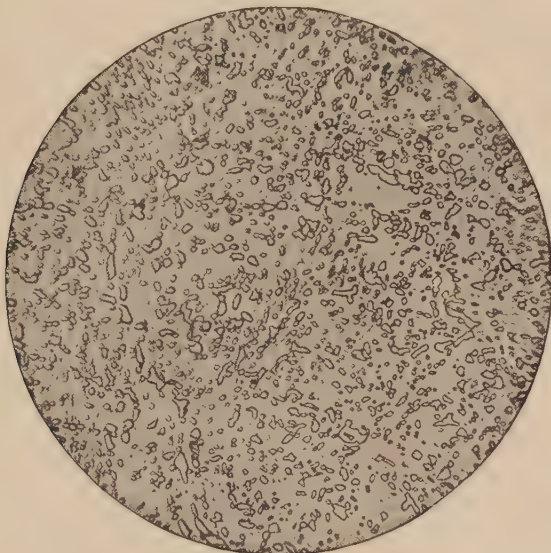


FIG. 33.—Granular pearlite, $\times 400$.

Steels containing sorbite have lower tensile strength and greater toughness than when composed largely of troostite but are stronger and have greater notch toughness than steels of pearlitic structure.

Sorbite changes to granular pearlite when annealed at a sufficiently high temperature for a long enough time. Granular pearlite is the structure which gives steel its best machining properties and is the one that it is desired to obtain in the usual annealing process.

Coarse Grain.—When steel is heated for a long time at a temperature above the point where the structure becomes austenitic, or if it is heated at a very high temperature, large crystals of

austenite will be formed. Then when this steel is cooled, very large ferrite grains will result. Large grains of ferrite are also obtained when steel is cooled very slowly. Such a coarsely crystalline structure gives steel poor mechanical properties, and to refine the structure and improve mechanical properties it is necessary to forge or anneal the steel.

RECRYSTALLIZATION

Cold-worked Crystals.—The crystal structure of cold-worked metal can also be changed by annealing. Cold-working causes the crystals to become elongated and when the cold-worked material is heated to a sufficiently high temperature the elongated crystals break up into small equi-axial grains which may then grow into larger grains if the heating is continued. The temperature necessary to produce this breaking up of recrystallization of the elongated grains is lower the greater the deformation of the crystals.

INFLUENCE OF MANGANESE, NICKEL, CHROMIUM, AND TUNGSTEN ON THE FORMATION OF THE MICROSTRUCTURE

Alloy Steel; Self-hardening Steel.—The presence of alloying elements may have a large effect on the structure of steel. Manganese and nickel, and to a less extent also chromium and tungsten, have a tendency to prevent the decomposition of austenite. Steels containing these elements in sufficiently large quantities may retain martensite or even austenite when slowly cooled. Steel which retains considerable martensite in slow cooling is called self-hardening steel.

Chromium and tungsten also reduce the solubility of carbon in austenite, so that ledeburite occurs with a lower carbon content in steels containing these elements than it does in straight carbon steels. In the latter steels at least 1.7% carbon must be present before any ledeburite can be formed. High-speed steel is an example of the lowering of the solubility of carbon by the addition of alloying elements. The presence of alloying elements also has a tendency to reduce the grain size and gives a smooth velvety fracture.

The diagram given in Fig. 28 is for pure iron carbon alloys only. When other elements are present it is necessary to determine the location of the transformation points by suitable tests. This has been done for the more common alloys so it will be fairly easy to determine the proper temperature for heat treating a new alloy.

CHAPTER III

THE MANUFACTURE OF AUTOMOBILE STEELS

THE TREATMENT IN THE MELTING APPARATUS

Automobile steels are produced almost exclusively in open-hearth and electric furnaces. Bessemer steel is used only for making sheet metal and unimportant fittings, etc. Alloy steels cannot be made by the bessemer process.

Steels containing small amounts of alloying elements may be made in the open-hearth furnace, since nickel does not burn and the small chromium content (1 to 1½%) causes little loss from combustion.

Open-hearth and Electric Furnace.—To produce good quality steel it is necessary to avoid over-oxidation of the metal during the melting and refining process. This can sometimes be done in the open-hearth process more readily than in the electric furnace process, and this explains why some kinds of steel from the electric furnace are inferior to those made in the open-hearth. This holds true particularly in the case of soft carburizing steels with about 0.15% carbon. The carbon in such steels must be reduced very low in the refining process with the result that, when ferro-chromium and ferro-manganese are added later, the carbon content will not be too great. In the open-hearth process the oxidizing action continues even after the addition of the ferro-chromium and ferro-manganese; therefore, the carbon content does not have to be reduced so low before the addition of these metals. An experienced electric furnace operator may be able to produce carburizing steel as good as or better than that made by the open-hearth process, by preventing over-oxidation. This can best be done by the addition of ferro-manganese in sufficient quantities so that the manganese content is always above 0.4%.

The difference between well made and over-oxidized steel shows up even in pouring, as the former looks much clearer.

Over-oxidized steel shows edge fissures when rolled although the analysis may be correct. The mechanical properties are much different, over-oxidized steel having poorer elongation and notch toughness.

Annealing steels have an average carbon content of 0.2 to 0.4%. They are best produced in the electric furnace because the molten metal can be left in the furnace longer after the addition of the alloying elements and the ferro-manganese. In the open-hearth process the metal must be poured very shortly after adding the alloying elements, otherwise chromium, manganese and carbon will be burned. Open-hearth steel is less pure in casting, shows more tendency for formation of blowholes, is more apt to have segregated chromium and chromium carbide, is apt to fissures in forging, and has greater annealing brittleness.

In Germany the basic electric furnace process is used for the production of high-class steels; the acid process is little known in spite of its advantages in melting. Dr. Müller-Hauff¹ has shown that the acid electric furnace is superior to the basic process both in quality of metal produced and in economy. Good scrap is required for the acid process, but in large works this could be had in sufficient quantities so that one furnace could operate continuously.

Deoxidation.—The operations of degasing and deoxidizing in the furnace determine the quality of a melt of steel. Chemical analysis shows only large variations so that a correct analysis does not mean that the steel is of good quality. There is no simple method of determining whether the metal has been melted properly or not. Poorly melted steel results in poor working properties in the finished metal, but the same poor properties may be caused by poor casting, forging, rolling or annealing and poor working qualities are not always the result of poor melting. Deoxidation can be carried out equally well by an experienced steel maker in either an open-hearth or electric furnace. The open-hearth furnace is not suitable for degasing, however; and here the electric furnace has the preference. The acid electric furnace process is most advantageous because the oxidizing and degasifying operations are carried out automatically.

Slag.—Besides deoxidation and degasification of the molten metal, it is important that the slag particles shall be removed.

¹ *Stahl u. Eisen*, 46 (1926), p. 213.

The slag and metal will be mixed somewhat during the tapping operation and it is necessary to let the metal stand for five to ten minutes after removal from the furnace, in order that the slag particles may rise to the surface. It is of course necessary to have the temperature of the metal, when tapped, high enough so it will not freeze when left in the ladle for the required time. Flaws and slags in steel result very often from improper control of the pouring temperature and the length of time in the ladle. It is impossible to avoid slag particles entirely and they will be found in the best steel. The number and size of the slag particles should be reduced to a minimum by leaving the metal in the furnace and ladle for the proper length of time.

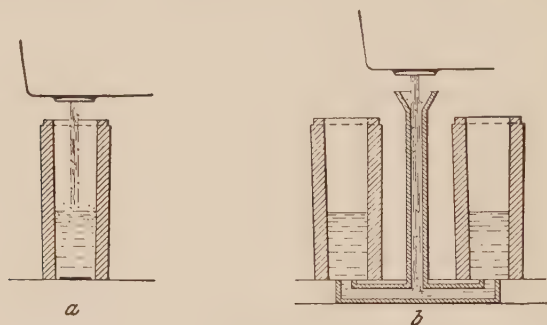


FIG. 34a and b.—Casting ingots from above and below.

THE POURING OF THE STEEL

Part of the slag may be present as a result of the casting operation itself. There are two methods of pouring castings: from above as shown in Fig. 31a and from below as shown in Fig. 31b. When pouring from above each ingot is filled separately. A plate of $\frac{3}{8} - \frac{3}{4}$ in. thickness is placed on the bottom to prevent the entrance of foreign material. When pouring from below, a number of ingots are filled at the same time through a funnel and pipes lined with heat resistant brick. The metal running through the pipes may remove small particles of the bricks and thus cause impurities. The location of the slag particles in the ingot depends upon the way in which the ingot freezes.

Solidification in Mold.—The solidification of the steel is accompanied by a reduction in volume. Solidification progresses in

layers from the walls of the ingot to the interior, as shown schematically in Fig. 35.

Segregation, Shrinkage Cavities or Pipes.—The shrinkage of the metal results in a cavity being formed in the head of the ingot. The form and size of this shrinkage cavity depend on various factors. The shrinkage cavity itself is not as undesirable as the segregation of harmful elements in the material around the cavity, which is the last of the metal to solidify. This segregation zone is composed of metal rich in such undesirable elements as sulphur and phosphorus and has a lower melting point than the rest of the metal.

Extended research on the size of the segregation zone has been done by Wüst and Felser¹ and also by Talbot.² The elements in the order of the extent to which they tend to segregate are: sulphur, phosphorus, carbon, manganese, and silicon. The maximum enrichment on the segregation zone for the different elements is shown in the following tabulation:

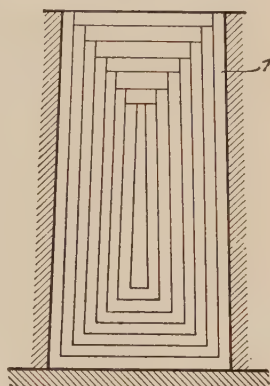


FIG. 35.—Schematic view of the formation of shrinkage cavities.

Element	Enrichment in Per Cent	
	After Wüst and Felser	After Talbot
Sulphur.....	139	337
Phosphorus.....	66	279
Carbon.....	26	150
Manganese.....	0	35

During the casting operation the slag is splashed to the surface of the ingot, where it solidifies and will do no damage because it is easily recognized and removed. However, there will be some particles of slag dispersed in the metal, especially around the shrinkage cavity or pipe, where they frequently cause flaws. Pipes therefore are undesirable not only because there are holes in the ingot but also because they are surrounded by metal of inferior

¹ *Stahl u. Eisen*, 30 (1910), p. 2154.

² *Journal of the Iron and Steel Institute*, 1905, II, p. 204. P. Oberhoffer, *Das technische Eisen*, p. 332.

quality and rich in slag. All means that reduce piping also reduce the amount of segregation.

As for the pouring method, pouring from above results in the formation of pipes in a more desirable location than does pouring

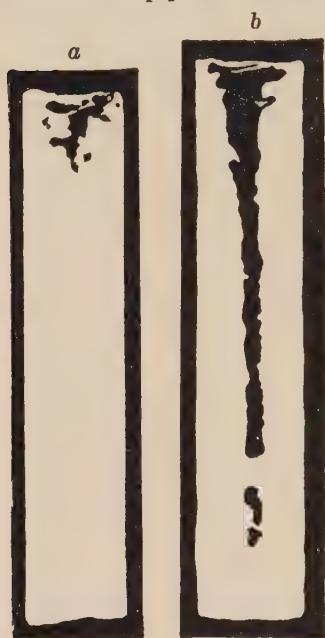


FIG. 36.—Shrinkage cavities.

from below. When pouring from above the hottest steel will be in the head and a flat, broad and open shrinkage cavity will be formed. When the ingot is poured from below the metal in the head is cooler, resulting in a hidden and far deeper cavity. (See Fig. 36b.)

In order to obtain an ingot such as shown in Fig. 36a, it is necessary to keep the metal at the top liquid as long as possible. This may be done by the following means:

1. By pouring from above. This has the disadvantage that the top of the ingot will be splashed and will have to be cleaned again.
2. By the form of the ingot. A form which is wider at the top is usual, although it is inconvenient to handle.
3. By use of fire brick caps, which cause the steel to remain liquid longer. The caps have to be coated after being used for a time, and may break off on the edges when put on the ingot and thus cause impurities.
4. By pouring liquid metal on the freezing head.
5. By keeping the head warm by means of a layer of charcoal. This charcoal may carburize the metal to a considerable depth.

Usually these methods will not entirely eliminate the cavity, and 5 to 20% of the ingot is cut off the upper end. Likewise the base, which is frequently torn on the edges, is usually cut off, the total discard being 8 to 30% of the ingot.

Pouring Temperature.—It is particularly important that the steel shall be poured at the correct temperature. Generally speaking, abundant heat should be used for melting but the least possible amount for pouring. Instruments are not available for measuring the temperature of the molten steel exactly; furthermore, the correct pouring temperature varies with the kind of steel, the size of ingot, charge, etc. When pouring from below it is possible to observe the surface of the steel during the pouring operation even for small ingots. A small skin of crystals should form on the walls of the mold during casting, starting when the metal reaches about two-thirds of the ingot height. This skin gradually grows toward the center and closes when the mold is completely filled. The condition described is especially important when pouring silicon steels. If the temperature is too low the skin forms earlier, closes too early, and may become too thick so that it sticks to the walls and is finally broken through by the molten metal, resulting in the so-called cold welding which later causes fissures. If the metal is too hot the skin forms late or not at all. Such ingots are usually full of blowholes, the steel is less tough and is badly segregated.

Gas Blisters, Gas Segregation.—Steel to which silicon is not added will always have blowholes and gas inclusions. Molten steel contains large quantities of dissolved gases that are given off on solidification. Around these gas bubbles that are trapped in the steel, a shell of freezing metal forms. As the temperature decreases the pressure of the bubbles decreases so that liquid material will be sucked in. This liquid metal is rich in harmful elements and thus bubble segregations are formed. When steel containing these bubbles is rolled the cavities will usually weld and so will not have a bad effect on the quality of the steel. Alloy steels do not weld readily when hot; therefore in making these steel aluminum or silicon (0.15–0.30%) is added to degasify the metal. These steels show chiefly the ingot form of segregation, the piping.

Segregation and Testing.—It is not possible to eliminate segregation by annealing. Segregation zones persist throughout the working and treating, and can be shown on longitudinal and cross-sections by suitable etching. Since the segregations may be considered as variations in the amounts of different alloying elements, especially of phosphorus and sulphur, in different parts of

the ingot or bar, they are of importance in taking material for testing or analysis. It is theoretically impossible to obtain exact average chemical composition regardless of whether the ingot is tested after pouring, rolling, or forging. Material from the top of the ingot will always show a larger percentage of phosphorus and sulphur. In order to eliminate so far as possible the effect of segregation upon the chemical analysis, the material to be analyzed should be taken from the whole section of the piece by milling, planing, or drilling.

The strength too is largely influenced by the presence of segregation, especially the difference in strength of test pieces cut crosswise and those cut lengthwise of the ingot. The difference between tests of specimen cut in these two directions is shown in Table IV.

TABLE IV.—ANALYSIS: 0.39 PER CENT CARBON, 0.68 PER CENT MANGANESE, 0.26 PER CENT SILICON, 0.025 PER CENT PHOSPHORUS, 0.030 PER CENT SULPHUR, 0.09 PER CENT COPPER

Ingot 330 lb. forged to bars $1\frac{3}{16} \times 8$ in.

Test pieces taken from the middle third where, as the etching showed, no excessive segregation existed

Relation of Tension to Fiber	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation Gage Length		Reduction, Per Cent	Notch- tough- ness, Ft.-lb. per Sq. In.
			10×Diam., Per Cent	5×Diam., Per Cent		
Lengthwise.	53.7	87.5	21.3	30.6	65.0	63.5
Lengthwise.	53.4	88.2	21.1	31.0	66.0	66.5
Crosswise...	52.5	88.8	11.5	13.7	35.5	11.7
Crosswise...	53.4	86.6	8.6	12.1	25.0	8.9

Influence of Fiber of Steel on the Strength.—The designer must consider how the stresses on a part are working with regard to direction of the axis of the original ingot. The proper location from which the test pieces should be taken must be considered in making tests. Even when such test bars are taken from the same direction in relation to the ingot, the properties may vary depending on whether the bars are from the segregation area or from the purer outer zone. In testing, it is usually necessary to determine the average properties. If a test piece is turned out

of a fairly large billet it will consist principally of the segregated core; thus it is evident that in the case of annealed material the billet should be forged down until it is of approximately the required size, when the machining will be reduced to a minimum. For heat-treated material this cannot be done since the properties of the small bar would not be the same as those of the larger piece after heat treatment.

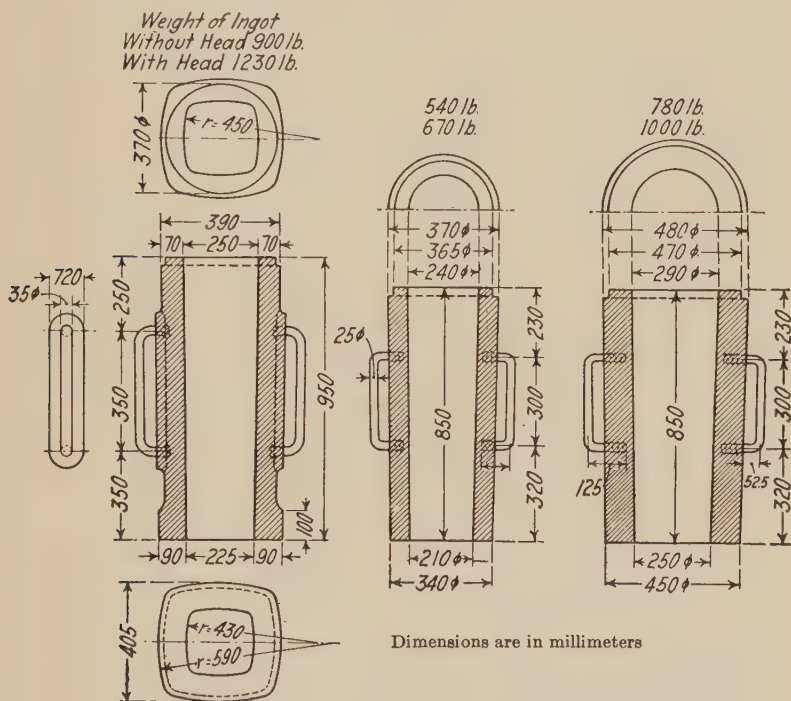


FIG. 37.—Ingot molds.

Form and Size of Ingot.—The formation of pipes depends greatly on the form of the ingot. Small ingots are usually better because they freeze faster and have less tendency to form shrinkage cavities and segregations. They are, however, less economical because they result in more waste. For automobile parts, which are generally fairly small, ingots of 700 to 1800 lb. will be sufficient; the lower weight ingots being used for steels with large amounts of alloying elements, for making such parts as valves. In order to get the surface of the ingot clean for the following operations,

it is advisable to use ingots with a round section that can be easily turned on a lathe. Small surface flaws, such as porous spots, slag on the surface, and fissures, can then be easily removed, thus preventing the formation of larger fissures during rolling or forging. It has been found more economical to turn the ingots than to plane or mill them. Steels of high alloy content, which are very sensitive on account of their rapid hardening properties, are best cast in round ingots up to 900 lb. Larger ingots with round cross-section are not recommended for high alloy content steels, since they tend to have axial fissures.

For the majority of steels, square sections with round corners, hexagonal or octagonal sections, with a weight of 900 lb. to 2200 lb. are used. They are practically immune to axial fissuring caused by too high a temperature and are good for rolling. Figure 37 shows the dimensions of molds used in German steel works for round and square ingots. The material used is hematite. It is necessary to clean the mold before each casting with iron brushes in order to remove any iron oxide that might be present and that would react with the carbon of the steel, producing gas blisters.

FORGING AND ROLLING

Ingots coming from the steel works are preheated preparatory to rolling or forging, and this preheating operation requires considerable skill. The higher the alloy content of the steel, the lower is its thermal conductivity, the greater its internal strains resulting from cooling after casting, and the more necessary it is to heat it uniformly and slowly. Large ingots (over 2200 lb.) are best put into the preheating furnace while they are still red-hot. Ingots which are heated too rapidly will show cross fissures; axial fissures are mostly due to unequal or too fast cooling.

In order to destroy the cast structure of steel and to eliminate blowholes, etc., it is necessary to reduce the section by about one-third by rolling or forging. There is still some question as to which of these methods is the better. In forging, the pieces are usually smaller and the temperature can be more easily controlled than is the case with the pieces that are rolled. This probably accounts for the better reputation of forged material. Steel of high alloy content is sometimes first forged and then rolled. Generally speaking, there is hardly any noticeable dif-

ference between the physical properties of material worked by the two methods.

Influence of Temperature on Forging and Rolling.—The best temperature for rolling and forging depends upon the chemical composition of the steel. For most machine steels the forging temperature is between 1100 and 800° C. (2000–1475° F.). Very soft steel may be heated to 1200–1250° C. (2200–2280° F.), so that the ingot will “drip,” in order to weld blisters and blowholes. The method of heating is of great importance. It should be slow at first in order to avoid stresses, especially below 700° C. (1300° F.). The temperature reached should not be so high or the time of heating so long that the structure of the steel is injured. Besides burning the steel, which might occur if the operator were very careless and which would ruin the steel completely, the structure might be coarsened to such an extent by leaving the steel too long in the furnace that the subsequent hot-working will not eliminate the coarse grain completely. This danger applies especially to small forgings that may sometimes be put in the furnace and not attended to until they are badly overheated.

It has long been recognized that the temperature at which the forging operation is completed has an important effect on the properties of tool steel. In the case of machine steels it has only been recognized that too low a finishing temperature results in fissuring and too high a finishing temperature results in a change in dimensions. However, it is just as possible to injure the properties of machine steel as it is to injure these of tool steel by incorrect final forging temperatures, although the harmful effects may be eliminated to some extent by subsequent heat treatment. The temperature at which forging is finished should be kept at 800° C. (1475° F.) and should never go below 750° C. (1380° F.), since steel, especially alloy steel, undergoes a cold-hardening effect when worked below the temperature and fissures are produced. Too high a finishing temperature results in a loss of toughness, especially of notch-toughness.

After hot-working, a steel part should be uniform in temperature. It should be stored in a dry and draftless place; alloy steel which tends to air-harden is best packed in hot ashes or placed in a warm furnace to cool. If the ingot is cut into blooms it is notched near the head and after cooling broken to check for piping. If the fracture is not satisfactory, the bloom is notched

hot 12 in. to 20 in. below and again broken until sound steel is reached.

Drop Forging.—The manufacture of forged and rolled bars offers little difficulty. The making of drop forgings is considerably more difficult, since only in the rarest cases is it possible to hammer bars right into the dies. Usually it is necessary first to preform the piece, which was cut to give the required weight, by forging under a hammer; then it is heated to about 1100° C. (2000° F.) and placed in the die. A fairly high temperature is used in order to obtain a good flow of the material and in order that it will fill out the die. Between the two halves of the die is left a little space to take care of excess material; thus the burr is formed (Fig. 38). The two halves of the die are placed in heavy drop hammers, and it will usually be necessary to give the piece several blows to make sure that the die is filled. The burr is removed by placing the piece upon a burring die and pressing it through with a punch, thus shearing off the burr. To obtain exact dimensions the piece is then put back into the forming die.

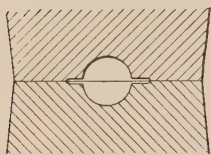


FIG. 38.—Die with burr-groove.

Faults in drop forging may have various causes. Aside from faulty form due to the die-halves being out of center, it is possible to find folds and overlaps caused by the rough piece of the die having the wrong form. These folds which are covered with oxide are hard to detect and result in cracks and breakage. The burr, which is only $\frac{1}{16}$ to $\frac{1}{8}$ in. thick, cools off during the forging operation while the body of the piece is still red hot. The strain caused by the temperature difference between the burr and the forge piece frequently results in cracks along the burr. The amount of working will often be insufficient to produce the best properties on account of the high temperatures used in drop forging. The main advantage of the process is that complicated parts can be produced in one piece without destroying the fiber of the steel.

Crankshafts.—Since the greatest strength is always in the direction of the fiber, it is attempted in drop forging to carry the fiber without interruption through the whole part. An example of this is the manufacture of crankshafts. Most crankshafts are made by bending a billet over a saddle and then drop forging it

into finished shape in a die. When only small quantities are needed it would not pay to make a die; therefore shafts are machined out. Figures 39a and 39b show etched sections of both

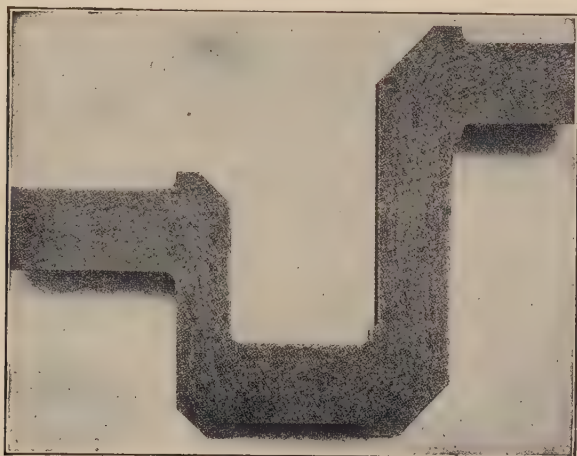


FIG. 39a.—Crankshaft, pre-bent over a mandrel and pressed into a die.

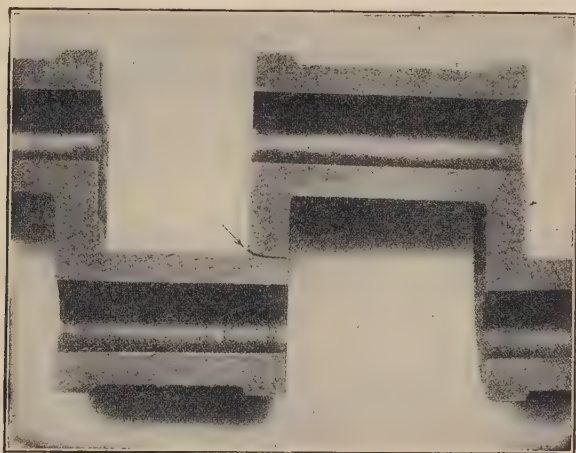


FIG. 39b.—Crankshaft throw cut out of the solid pre-forged blank.

machined and forged shafts, and it will be seen that in the case of the forged shaft the fibers follow the form of the shaft whereas in the machined shaft they are cut. Bending and drop forging is much cheaper than machining in quantity production.

The trend towards smoother running motors led to the development of six- and eight-cylinder engines. A big difficulty was the production of crankshafts. Four-cylinder engines have the cranks all in one plane whereas the six cranks are placed at 120 deg. and the eight cranks at 90 deg. The cranks are now bent in one plane and then twisted to the correct angles. This twisting is done principally in one of the bearings, which is thus subjected to a heavy deformation, sometimes causing cracks.

Testing of the Bars.—Steel bars after rolling and forging are checked carefully. The method of testing blooms for pipes and cavities has been mentioned before. In some cases, especially for ball-bearing steel, the finished bars are tested for pipes and inclusions by cutting a disk from the finished bar, hardening and breaking it. On the fracture thus obtained inclusions are easy to find. If they are small they will do no harm, especially if the material is to be used for the rings of the bearings; in this case the core is removed anyway.

The surface should be carefully checked while the steel is still in the form of a billet. Surface cracks may be removed with an air-hammer, or better, by grinding, since the ground surface shows more clearly when the crack is entirely removed. In grinding, the work should not be pressed too hard against the wheel, or too much heat may be generated. When grinding sensitive material, such as chromium-nickel air-hardening steel, it should be heated to 300° to 400° C. (570° to 750° F.) in order to avoid cracks. Grinding is also resorted to when burrs cannot be removed well enough in a die. This also shows up possible cracks near the burr.

In the case of some steels, especially of the soft chromium-nickel type, the scale formed in rolling does not fall off but sticks to the bars and is rolled in. This scale is frequently removed by scraping or brushing, or by compressed air or steam immediately before passing through the rolls. Plain carbon steels do not need to be treated in this way since the scale chips off under pressure.

Annealing of the Bars.—All steels except common straight carbon steels are annealed after hot-working. The object of this annealing is to remove the internal stresses caused by uneven temperature or too fast cooling, and to make the steel uniformly as soft as possible. Uniformly soft steel is desirable because the cutting speed and wear of tools depend on the hardness, and

because the correct tolerance cannot be maintained if the hardness is not uniform. Annealing is done by putting the steel into metal boxes in a furnace, heating from six to twelve hours, depending on the hardness of the steel, and then cooling down to 300° C. (510° F.) in the closed furnace. The boxes are pulled out and opened when this temperature is reached. If there is no danger of decarburizing the material, it may be annealed in the furnace without putting it into boxes.

It is common practice in Germany to anneal at a temperature near the lower transformation point in order to get the pearlite in the spheroidal form, which is the most uniform in structure and best for machining. To obtain the pearlite entirely in this form, it is necessary to anneal for a considerable period of time at the proper temperature. Since the transformation point varies with the chemical composition, the annealing temperature is different for different kinds of steel. The lower the annealing temperature, the more difficult is it to anneal. Table V gives the annealing temperature for a number of steels.

TABLE V.—ANNEALING TEMPERATURE FOR VARIOUS STEELS

Carbon, Per Cent	Manganese, Per Cent	Silicon, Per Cent	Chromium, Per Cent	Nickel, Per Cent	Annealing Temperature
Up to 0.50	Up to 1.0	.....	.....	.....	650-700° C. (1200-1300° F.); the softer the nearer to 650° C. (1200° F.)
0.5-1.0	Up to 1.0	.....	.....	.....	700-720° C. (1300-1330° F.)
0.4	About 0.5	1.0	.....	.....	720° C. (1330° F.)
0.4	About 0.5	1.0	1.0	.....	740° C. (1365° F.)
Up to 0.4	About 0.5	.....	1.0	.....	680-700° C. (1260-1300° F.)
About 1.0	About 0.5	.....	1.0-1.5	.....	720° C. (1330° F.)
Up to 0.4	About 0.5	.....	.....	Up to 2.0	640-670° C. (1185-1240° F.)
Up to 0.4	About 0.5	.....	.....	2.0-3.5	600-640° C. (1110-1185° F.)
Up to 0.4	About 0.5	.....	.....	3.5-5.0	580-620° C. (1080-1150° F.)
Up to 0.15	About 0.5	.....	Up to 0.8	Up to 3.5	550-620° C. (1020-1150° F.)
Up to 0.15	About 0.5	.....	0.8-1.2	3.5-5.0	Max. 540° C. (1005° F.)
0.25-0.40	About 0.5	.....	0.6-1.0	3.0-4.0	600-620° C. (1110-1150° F.)
0.35-0.45	About 0.5	.....	1.0-1.5	4.0-6.0	540° C. max. (1005° F.)

Measurement of the annealing temperature is done with a thermocouple in the roof of the furnace. The operator must judge the temperature of the material being annealed by comparing the color of the annealing box with that of the protection tube of the thermocouple and should see that the heating is uniform and that the temperature is not allowed to get too high.

Since the temperature at the bottom of the annealing box will always be 30 to 50° C. (80 to 120° F.) less than at the top, it is common practice to put steel which requires a lower annealing temperature in the bottom of the boxes.

Normalizing.—Some specifications call for normalized steel, especially for scientific research. Normalizing is done by heating

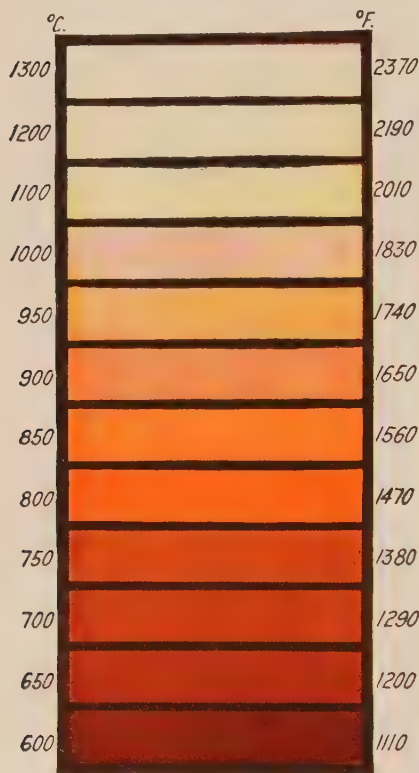


FIG. 40.—Temperature colors.

the steel above the upper limit of the transformation range so that it is entirely converted to austenite, and then allowing it to cool in air. The mechanical properties depend upon the rate of cooling, which is apt to vary somewhat so that normalized steel does not always offer a basis for ready comparison.

After annealing, a hardness test is usually made on the steel, and in addition it may be inspected for surface defects.

Welding.—The development of welding has brought about many new problems. Common fire welding, without flux, is possible only when using straight carbon steels, and, in addition, is not suited to mass production. The important industrial methods of welding

are the acetylene and hydrogen-gas welding processes, and the electrical-resistance and electric-arc methods.

In all of the latter processes, the metal is heated until it is fluid and the two parts form a continuous piece. The surface to be joined must be clean and free from oxides, etc. The quality of the steel is of great importance, since poorly deoxidized steel reacts with the flame, forming a joint with many craters. The

local high heating may cause stresses in the metal near the weld and also result in a coarse grain structure in that region. To restore the original properties of the metal as much as possible it is advisable to anneal for a time at 900° C. (1650° F.), or still better, to cool the weld rapidly and then anneal at high temperature. The physical properties, that may be obtained with material containing 0.25% C, 0.51 Mn, 0.025 P, 0.033 Si, 0.12 Cu are listed in Table VI.

TABLE VI.—PROPERTIES OF WELDED AND ANNEALED MATERIAL

	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Material before welding	44.6	69.3	26.3	33.5	64.5
Welded (fissure in the weld)	35.1	62.4	11.2	14.3	25.7
Annealed at 900° C. (1650° F.), cooled in air.	39.3	65	15.9	20.6	47.8
Welded at 850° C. (1560° F.), hardened in water, annealed at 650° C. (1200° F.) for ½ hour	46.9	67.5	24.8	30.6	59.5

There have been only a few investigations on the effect of the composition of steel upon the weldability.

There is no method of testing a weld in a finished piece and this fact is probably responsible for the former lack of confidence in welded material. However, modern welding practice makes it possible to obtain a high degree of uniformity and dependability and the process should have a very good future.

COLD DRAWING, COLD ROLLING—ADVANTAGES AND DISADVANTAGES

Cold Rolling and Cold Drawing.—Steel which must be perfectly straight and close to size, as for example that used in screw machines, must be cold-rolled or cold-drawn, since hot-worked

material will not meet these requirements. However, cold-working causes considerable decrease in toughness and increase in hardness, although the reductions in cold-working are never very high. Goerens¹ has investigated the properties of cold-drawn steel and found those given in Table VII.

TABLE VII.—PROPERTIES OF COLD-DRAWN STEEL

(After Goerens)

Material	Mechanical Treatment	Figure Indicating the Preceding Cold Working, Per Cent	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Reduction, Per Cent
Thomas-steel	Rolled wire, 0.204-in. diam.					
C =0.07	Natural hard	.....	40.3	59.6	30.6	73.0
Mn =0.48	1 draft	41.6	92.0	94	8.5	45.0
Si =0.006	2 draft	70.5	.....	118	6.2	31.0
P =0.080	3 draft	79.5	.....	131	6.0	29.0
S =0.056	4 draft	85.7	.....	135	6.3	30.0
	5 draft	89.2	.....	142.5	5.7	25.0
	6 draft	93.2	.....	148	4.9	20.0
	7 draft	95.2	.....	154	5.2	25.0
	8 draft	96.5	.....	(153)	.....	(20.0)
Martin-steel	Rolled wire, 0.21-in. diam.					
C =0.55	Natural hard	.....	52.5	93	23.3	38.0
Mn =0.47	1 draft	34.0	133.9	140	6.8	19.4
Si =0.262	2 draft	55.0	.....	158.3	5.9	15.3
P =0.068	3 draft	62.6	.....	170	6.5	14.0
S =0.036	4 draft	78.6	.....	190	6.0	14.1
	5 draft	86.5	.....	225	6.3	13.4
Martin-steel	Rolled wire, 0.208-in. diam.					
C =0.78	Natural hard	.....	75.4	115.2	19.2	36.0
Mn =0.38	1 draft	25.4	.....	144.5	7.6	24.2
Si =0.113	2 draft	36.7	.....	155	6.9	19.8
P =0.016	3 draft	47.5	.....	172	5.2	20.2
S =0.019	4 draft	58.5	.....	180	6.2	17.5
	5 draft	67.5	.....	182.5	6.0	15.5

¹ *Stahl u. Eisen*, 33 (1913), p. 438; further G. Mars, *Die Spezial Stähle*, p. 188.

As an example, from material as traded commercially an analysis shows that a steel with 0.45% carbon, 0.74% manganese, 0.21% silicon, 0.032% phosphorus, 0.022% sulphur, 0.15% copper has the following properties:

TABLE VIII.—EFFECT OF A SINGLE DRAFT ON ANNEALED MATERIAL

Treatment	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Annealed, 0.865-in. diam.	46.5	87.3	22.2	30.7	54.8
Drawn to 0.786-in. diam.	112.5	116.8	5.8	7.9	23.0

The steel in this table was rendered useless by cold-working, since it lost all its toughness. The strength and elongation of cold-worked material are apt to be non-uniform in addition to the great loss in toughness. The toughness of cold-drawn or cold-rolled steel may show a decrease with time over a period of several months, the same change taking place in a much shorter time if the material is heated to 100 to 200° C. (212 to 392° F.). Alloy steels show the same changes on cold-working distinctly, but to a much less degree.

Annealing after Cold-rolling.—The hardening and loss of toughness caused by cold-working may be removed by annealing. Delbart¹ has published the interesting results of some experiments on the effect of cold-working and annealing. His steel had the following composition shown in Table VIII.

TABLE IXa.—RESULTS OF COLD-WORKING AND ANNEALING AT VARIOUS TEMPERATURES

Analysis

Steel	Carbon C	Manganese Mn	Silicon Si	Phosphorus P	Sulphur S
No. 1	0.127	0.44	0.06	0.019	0.033
No. 2	0.39	1.07	0.21	0.032	0.020
No. 3	0.60	0.64	0.119	0.020	0.017

¹ *Comptes rendus*, 180 (1925), p. 934; further *Stahl u. Eisen*, 45 (1925), p. 1715.

The pieces were stretched, then annealed at 450 to 850° C. (840 to 1560° F.) for ten minutes, and cooled. The strength and elongation are shown in Table IX.

TABLE IXb.—RESULTS OF COLD-WORKING AND ANNEALING AT VARIOUS TEMPERATURES

(By Delbart)

Steel		Drawn	Annealed at Temperatures							
			400 750	500 930	550 1020	600 1110	650 1200	700 1300	750 1380	800° C. 1470° F.
No. 1	Strength, 1000 lb. per sq. in.	77.3	75.5	67	64	58.8	50.6	51.2	53.5	52.5
	Elongation, per cent.	7.0	12.0	17.5	19.5	23.5	34.0	34.0	31.0	31.0
No. 2	Strength, 1000 lb. per sq. in.	111.0	107.8	105	102	98.4	90	84	89	93.5
	Elongation, per cent.	7.0	10.0	11.5	13.5	15.2	18.7	23.0	20.5	22.5
No. 3	Strength, 1000 lb. per sq. in.	124.8	120.8	117.5	109	99	92.2	92.5	106	107.3
	Elongation, per cent.	6.0	7.0	11.0	13.0	17.0	21.0	19.0	17.0	15.0

The strength is seen to decrease while the elongation increases with increasing annealing temperature, until at 650 to 700° C. (1200 to 1290° F.), the correct annealing temperature, the steel is in its softest state. If the steel is annealed at a higher temperature, a rehardening will occur on cooling as a result of the faster cooling rate.

A very small reduction by cold-drawing after annealing will make the metal hard and brittle again. Final cold-drawing to obtain accurate shape and size cannot be used for material which must be in a soft state when finished. To obtain close size-limits on such material, therefore, it is cold-drawn to finish size and then carefully annealed to avoid the formation of scale. The annealing is done by packing the pieces in receptacles, covering them with chips, and then luting the covers of the receptacles on so that they are air-tight. The bars have to be straightened by hand or in presses or straightening machines.

Cold-working is satisfactory for parts that are to be case-hardened since the latter process removes the stresses caused by the cold-work.

Strips.—Cold-rolling is used to a considerable extent in the production of steel strips to be used in quantity production on presses, where accuracy in dimension is necessary. The metal is first hot-rolled, then pickled to remove the scale, as in the case of bars and wire, and then cold-rolled to the finished size. By varying the degree of cold-working, sheets of different hardness can be obtained. Stampings from sheet metal are largely used in the production of bicycles, but much less used in automobile manufacture, where alloy steel stampings could be used to a greater extent.

Recrystallization.—The annealing of cold-worked steel at a sufficiently high temperature causes the metal to recrystallize. The cold-working deforms the crystals, and if severe enough breaks them up. Then when the metal is heated to a certain temperature, new crystals form, the size of the crystals depending on the degree of deformation of the metal, and on the annealing temperature. A recrystallization which transforms the metal to austenite may be obtained by annealing above the transformation temperature, but this is necessary only when the recrystallization of the deformed crystals at the lower temperature results in a too coarse grain structure. The recrystallization temperature of cold-worked straight carbon steel is always lower than the transformation temperature.

Machinability.—An important property of steel is the workability which depends not only on the strength, but also to a considerable extent on the toughness. It is a well-known fact that steel with a tensile strength of 185 000 lb. per sq. in. and an elongation of (10×) 8% is easily machined, whereas a high chromium-nickel air-hardening steel with 140 000 lb. per sq. in. tensile strength and (10×) 12% elongation is much harder to machine. Austenitic manganese steels (1.0% C and 13.0% Mn) with a strength of only 114 000 lb. per sq. in. and elongation of 40% are almost impossible to cut. It was found that if the hardness of these steels was increased by very slow cooling, from 850 to 300° C. (1560 to 570° F.) in five weeks, it was possible to plane them. Very soft tough steels are difficult to machine and especially to obtain a clean cut on.

The addition of phosphorus to soft steels makes the chips break off better and gives better cutting qualities, as does also the addition of sulphur. Especially pressed nuts are made from

a phosphorus steel of 0.04 to 0.06% carbon, 0.30 to 0.50% manganese, 0.20 to 0.60% phosphorus, and 0.05% sulphur. Sulphur is used in amounts up to 0.2% but has the disadvantage that it causes the steel to break in rolling. The best method of obtaining clean cutting properties is to add 0.2 to 0.8% silicon,¹ and this amount will be found in nearly all straight carbon and alloy steels. The silicon also makes the steel denser. The cold hardening of cold-drawn or cold-pressed soft steels also makes these steels easier to machine.

The wear of tools is greatly affected by the presence of scale on the surface of the material being machined, and for that reason drawn material is preferred. Forgings are cleaned by sand-blasting before machining.

Fatigue Strength and Surface Smoothness.—The condition of the surface has a great influence upon the durability of the parts, especially when they are subjected to alternating or repeated stresses. W. B. Thomas² gives the following figures showing the effect of surface finish on the resistance fatigue stress:

LOSS OF RESISTANCE TO FATIGUE STRESS

	Per Cent
Turned.....	Up to 12
Roughed with coarse file.....	Up to 20
Finished with fine file.....	Up to 7.5
Polished with No. 3 emery.....	Up to 6.0
Polished with No. 1 emery.....	Up to 3.0
Finish ground.....	Up to 4.0

Parts that are to be subjected to frequent change in stress must be finished with great care, since even the smallest mark may be the starting point for a fatigue break. Attempts have been made to eliminate the notching effect by pickling after machining. The experimental results were very promising but no reports of results obtained in actual practice have yet been published.

¹ *Recent additional note of the authors:* This means has proven very satisfactory; it is now possible to produce these steels in a quality which is best suited for screw machines. After information given by the manufacturer, Kloeckner Werke, Haspe, this free cutting steel can be machined with a cutting speed of 400-460 ft. p. min., a feed of 0.012 in. at a cut of 0.157 in.

² *Engineering*, 116 (1923), pp. 449, 483; *Stahl u. Eisen*, 44 (1924), p. 473.

CHAPTER IV

THE AUTOMOBILE STEELS

1. THE COMMON CARBON STEEL

In parts which are not subjected to very large stresses, the use of alloy steels would not give much saving in weight, and so the common straight carbon steels are used. In such steels, as used in automobile construction, the carbon does not usually exceed 0.60% and the manganese 0.80%. The properties of carbon steel have been tabulated by Mars¹ as in Table X.

Table XI is more convenient. The figures given are for annealed material. In the case of forged and rolled material the dimensions of the pieces have considerable influence since they affect the rate of cooling. Small parts usually have higher strength, but only slightly higher elongation, than heavier parts. In order to obtain readily comparable figures with carbon steel, the parts should be softened by annealing before testing.

Straight carbon steel on account of its low strength can be used only for parts subjected to small stresses. Steel with 0.25 to 0.45% C, 0.40 to 0.80% Mn, and 0.20 to 0.30% Si, is used for shaftings, axles, spindles, cones, levers, etc. It is very tough, but on account of its low yield point can not be used for parts subjected to changing or repeated stresses.

Most of the low-carbon machinery steel is used for making stampings. Very soft steel cannot be machined neatly with cutting tools, and therefore can be used only where a rough surface is not a disadvantage. The use of such steels in automobile manufacture is quite limited. As mentioned before, in order to obtain smooth machining properties, silicon is added, or, as in the case of pressed nuts, phosphorus.

Screw Steel.—Screw steel which is made with from 0.15 to 0.25% C and 0.5 to 0.8% Mn has a strength of 50 000 lb. per sq. in.

¹G. Mars, Die Spezialstähle.

TABLE X.—PROPERTIES OF COMMON CARBON STEELS (After Mars)

COMPOSITION			FORGED			ANNEALED		
Carbon	Silicon	Manganese	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elonga- tion, Per Cent	Reduc- tion, Per Cent	Yield Point, 1000 Lb. per Sq. in.	Strength, 1000 Lb. per Sq. In.
0.07-0.15	0.06-0.15	0.20-0.40	28-36	50-57	28-32	60-70	26-36	50-57
0.15-0.30	0.05-0.25	0.25-0.75	28-57	57-71	20-28	50-65	28-50	50-64
0.25-0.40	0.07-0.20	0.25-0.60	26-43	64-78	20-25	45-60	31-38	64-71
0.36-0.44	0.05-0.12	0.30-0.60	26-43	71-85	18-22	45-55	33-40	71-85
0.40-0.45	0.08-0.16	0.25-0.50	26-47	77-88	18-24	40-45	36-43	71-78
0.45-0.48	0.08-0.16	0.30-0.40	26-50	78-92	16-18	36-42	36-43	78-85
0.45-0.50	0.05-0.20	0.35-0.60	26-50	85-99	15-20	35-42	36-50	78-93
0.45-0.55	0.06-0.20	0.40-0.65	43-50	85-99	15-20	30-40	37-46	78-93
0.50-0.60	0.05-0.20	0.30-0.60	43-50	92-107	12-20	30-40	38-50	85-99
0.55-0.65	0.09-0.15	0.35-0.60	43-50	99-107	13-16	25-35	36-43	85-99
0.55-0.60	0.08-0.16	0.50-0.70	43-54	99-114	13-18	27-44	38-47	93-107

TABLE XI.—PROPERTIES OF ANNEALED COMMON CARBON STEELS

COMPOSITION		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	ELONGATION.		Reduction, Per Cent
Carbon	Manganese			10 × Diam., Per Cent	5 × Diam., Per Cent	
Up to 0.05	Up to 0.40	21-26	46-50	30-35	40-48	70-80
0.05-0.10	0.40-0.50	26-34	50-54	30-33	38-45	70-75
0.10-0.20	0.40-0.60	34-40	54-64	28-30	34-38	65-70
0.20-0.30	0.40-0.70	40-44	64-74	24-28	30-34	60-70
0.30-0.40	0.60-0.80	43-50	74-85	20-25	25-30	45-55
0.40-0.50	0.60-0.80	50-64	85-100	18-21	22-29	45-60
0.50-0.60	0.60-0.80	57-64	100-107	15-19	19-26	40-50

and an elongation of 30%. This steel, which is made in the open-hearth furnace, has a maximum sulphur and phosphorus content of 0.05%. It is suitable for screws that are not subjected to a very high stress.

Opinions differ widely as to the kind of steel to be used for screws. Some plants use common soft steel for screws up to $\frac{1}{2}$ in., and soft steel with 1% phosphorus for larger sizes. American automobile manufacturers often use case-hardened screws. The German standards DIN 1613 recommendations for screws are given in Table XII.

TABLE XII.—DIN STANDARD 1613 FOR SCREWS

Designation	Strength, 1000 Lb. per Sq. In.	Elongation, at Diameters						
		$\frac{5}{16}$ in. and over		$\frac{1}{4}$ in. to $\frac{5}{16}$ in.		$\frac{3}{16}$ in. to $\frac{1}{4}$ in.		
		10×, Per Cent	5×, Per Cent	10×, Per Cent	5×, Per Cent	10×, Per Cent	5×, Per Cent	
St. 38,13	54 to 64	20	25	18	22	15	18	Bending test DIN 1605. Loop for 180-deg. angle 0.5 <i>a</i> inside. <i>a</i> = thickness of test piece

Steel for Sheet Metal and Rivets.—For sheet metal and rivets, soft steel, with 0.05 to 0.1% carbon, about 0.4% manganese, and sometimes 1 to 2% nickel to increase the toughness, is usually used. For pressed parts, water jackets of cylinders, and exhaust pipes, Oberhoffer ¹ gives the following composition: 0.05 to 0.15% C, 0.03 to 0.06% Mn, 0.045% P, 0.045% S. However, fatigue failure caused by scratches from machining and by poor annealing between the drafts was encountered in using this steel. Instead of the phosphorus content mentioned above, White ² suggests for

¹ P. Oberhoffer, *Das technische Eisen*, p. 482.

² *Forging, Stamping, Heat Treating*, Sept. 1923, p. 408-16.
Stahl u. Eisen (1924), p. 990.

sheet metal, with the usual analysis of 0.10% C, 0.40% Mn, 0.035% S, a higher content of phosphorus, say 0.05% for heavier sheet metal, and 0.08% for thinner stock. The higher phosphorus content should give a smooth surface, and the same effect could be obtained by increasing the amount of carbon.

Deep-drawing Sheet Metal.—Sheet and strip steel are being used at a steadily increasing rate in automobile manufacture. Various kinds of steel are used in these forms. The sheet metal with the greatest ductility is that used for deep drawing, which usually has about the following analysis: carbon 0.10% max., manganese 0.35 to 45%, silicon, sulphur and phosphorus each 0.03% max. To determine whether this steel is suitable for deep drawing, the analysis cannot be relied upon and the steel must actually be tested in use or with the Erichsen machine. The tensile test may be used before rolling to determine if the material is suitable for deep drawing. The elongation for a gage-length 10 times the diameter must be at least 32%, or for 5 times the diameter 44%.

Blisters in Tinning.—Sometimes the surfaces of parts made from sheet metal are to be tinned, nickel plated, or enameled, etc. Such material may have to be rejected due to the formation of blisters that occur in the last operation only. These blisters may form when the material is rolled very thin, usually less than $\frac{1}{16}$ in., then annealed and pickled. They may form also when the sheet is heated for tinning, in which case they come out during the plating operation. The blisters are usually very numerous and very small and will be found without exception on all sheets of the same melting. There are many theories as to their cause, but in spite of many experiments no immediate cause has been found nor a way for preventing them. Most steel plant men believe that the cause is to be found in the steel plant. The only safe way of avoiding the blisters is to take one bloom from the melting, roll it out and put it through the regular finishing operation. If no blisters develop, it may be safely concluded that the whole lot is good.

Cold-rolled Strips.—Cold-rolled strip steel has many advantages as compared to sheet metal. It can be rolled to closer size limits and thus gives less waste at the ends, and in addition it has a polished surface from the cold-rolling which can be retained by a suitable annealing process. When strip steel is

cold-rolled it is hardened to an extent depending on the amount of cold-rolling. There are thus different hardnesses, referred to as $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, etc., but they have not been expressed in terms of actual physical properties. The material is the same as common soft steel in composition and owes its hardness to the cold-working only. There are many purposes for which it can be used.

Steel for Wire.—A large amount of soft steel is converted into wire. The hot-rolled rods are cold-drawn to the desired size, with anneals at suitable points between the drawing steps to give the proper working properties and final strength. Wire is sometimes subjected to a so-called patenting process to give it certain physical properties. This process consists of an annealing operation followed by cooling in a lead bath.

Steel for Pressed Nuts.—The material for making pressed nuts occupies a special place among the alloy steels. This steel, which is made by the Thomas process or in the open hearth, usually has the following composition: 0.04 to 0.06% C, 0.4 to 0.8% P, 0.3 to 0.5% Mn.¹ It must not be too soft or too hard, and should give a short crumbling chip which will not smear and permits the cutting of threads with less wear on the tools.

The phosphorus content greatly affects the hot-working properties of steel. It has been found that high phosphorus metal fills the die much better in pressing and gives sharp edges. It was formerly believed that coarse-grained material was required for pressing, but it has been found that it is impossible to make pressed nuts with a fine-grained structure from coarse-grained steel. The grain size probably depends upon the size of the ingot, but investigations which have been started recently on this subject have not yet been completed and the matter has not been definitely settled.²

Silicon Steel.—Silicon steel has again been introduced during the past three years as a machinery steel.³ Its excellent qualities

¹ E. Faust, *Stahl u. Eisen*, 45 (1925), p. 1701.

² Recent additional note of the authors: The size of the grains is mostly a function of the temperature at pressing. On the common presses a number of nuts are pressed in one series from a bar. The first nut from the hot end will have a coarse structure, and the last nut with the low temperature will have a fine structure. This difference in grain size results in differences in toughness. But for common nuts differences in toughness are negligible. If particularly tough nuts are required, a steel with low phosphorus content should be chosen, because in this steel the grain size will not vary so much with the temperature. It is of course wrong to judge steel for pressing nuts by the structure of the bar, since this structure depends upon the rolling temperature.

³ *Stahl u. Eisen*, 46 (1926), p. 493.

were known long ago but it was not available in large quantities. This steel has the following analysis: 0.1% C, 0.5 to 0.8% Mn, 0.7 to 1.0% Si, and the following strength:

Yield point.....	48 000-54 000 lb. per sq. in.
Strength.....	68 000-75 000 lb. per sq. in.
Elongation (gage length 10× diam.).	26-32%
Reduction.....	60-65%

The high yield point is particularly noticeable, being 60 to 70% of the tensile strength, whereas for the common carbon steel it is only 50 to 60% of the strength. This steel also gives good values for the elongation and reduction of area. It has given good results in railroad work, but has not been adopted to any considerable extent in automobile construction.

Steel Castings.—Hot-forming is too expensive for parts which do not require considerable strength, and these are made as steel castings. Steel castings of course lack the improved properties that are imparted by the rolling and forging operation. Thus the grain size is coarser, resulting in a lower yield point, greater elongation, reduction of area, and toughness. It is possible to refine the grain somewhat by annealing, and in this way to improve the properties. Cast steel analyzing as given in Table XIII, showed on annealing the changes indicated in the table.¹

TABLE XIII.—PROPERTIES OF ANNEALED CAST STEEL

Cast steel analyzed as containing 0.27% C, 0.88% Mn, 0.28% Si, 0.032% P, 0.04% S.

Annealing Temperature		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Reduction, Per Cent
Deg. C.	Deg. F.				
Non-annealed		33	67	14.6	17.0
750	1380	32	66.5	8.1	14.24
800	1470	34	70	20.7	28.2
850	1560	40	73	22.5	29.7
900	1650	38	72.5	20.0	26.7
1000	1830	37	74	14.0	20.4

¹ R. Schäfer, Die Konstruktionsstähle u. ihre Warmbehandlung, p. 220.

Cast steel analyzed as containing 0.26% C, 0.80% Mn, 0.25% Si, 0.0270% P, 0.030% S

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Reduction, Per Cent	Notch Toughness, Ft.-lb. per Sq. In.
Non-annealed. . . .	34.5	54.5	5.1	5.3	129.5
	32.5	67.6	23.3	27.7	153
	32.5	63	11.0	9.6	132
At 850° C. (1560°F.) annealed	38.5	67	22.4	36.0	421
	40.5	69	26.9	45.3	421
	42.5	69	23.8	40.1	393

Annealing of Steel Castings.—The proper annealing temperature varies with the carbon content. The A. S. T. M. gives the following temperatures: ¹

Per Cent Carbon	Annealing Deg. C.	Temperature, Deg. F.
0.12	875–925	1500–1700
0.12–0.29	840–870	1545–1600
0.30–0.49	815–840	1500–1545
0.50–1.00	790–815	1450–1500

The chart shown in Fig. 41 shows the temperature at a glance.

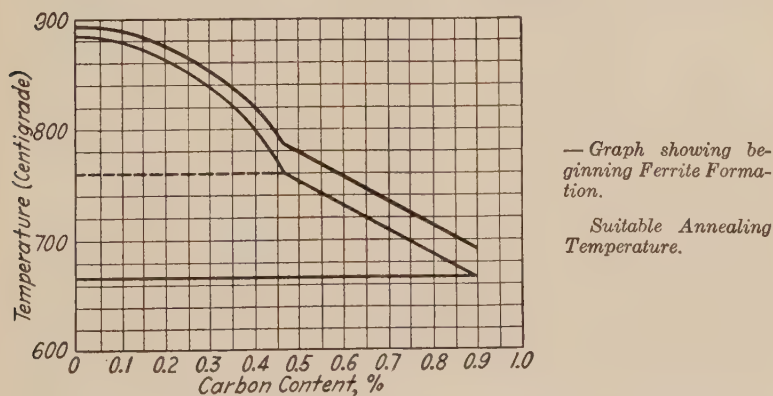


FIG. 41.—Suitable annealing temperature of cast steel with 0.8 per cent manganese.

¹ Schäfer, Die Konstruktionsstähle, p. 224.

If the walls of the casting are thin, the rate of cooling may be sufficiently rapid to give a fine-grained structure in the first place and annealing is not necessary. The cooling rate necessary to accomplish this depends upon the carbon content. The limiting wall thickness, below which annealing is no longer necessary, is given by P. Oberhoffer and F. Weisgarber¹ for the following carbon contents:

Carbon, Per Cent	Wall Thickness, In.
0.0	$\frac{3}{8}$
0.1	$\frac{7}{16}$
0.2	$\frac{1}{2}$
0.3	$\frac{3}{4}$
0.4	$1\frac{1}{16}$
0.5	$1\frac{1}{2}$

The castings should not be annealed too long or a coarse-grained structure will result. It is only necessary to hold the annealing temperature until they are heated uniformly throughout. The rate of cooling has an important effect on the structure. A very fine structure could be obtained by rapid cooling, but this might cause dangerous cracks. It is best to regulate the cooling temperature as follows: the heat is shut off after the castings have all reached the annealing temperature and cold air is let into the furnace; then when the temperature has dropped to a dark red heat, the furnace is closed and the parts are allowed to cool slowly to room temperature.

Annealing has such obvious advantages that no well-managed foundry will neglect it, yet many castings are still shipped without annealing. Annealing results in greater uniformity, removes stresses, and improves the toughness, gives higher elongation and reduction of area, and also raises the yield point.

German Standards for Steel Castings.—The German standard DIN 1681 gives the values of certain properties for steel castings that are shown in Table XIV. By requiring the minimum elongation it is not necessary to specify the maximum strength. The rupture elongation is given in the table for a gage length 5 times the diameter. The tests are made on pieces cast to the part, or when it is not possible to cast them to the part, they may be cast from the same melt. The results of these tests cannot be depended upon to give the properties of the parts, but only to

¹ *Stahl u. Eisen* (1920), p. 1437.

TABLE XIV.—PROPERTIES OF STEEL CASTINGS (DIN 1681)

Quality Designation	Properties Guaranteed				
	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length 5 × Diam., Per Cent Minimum	Magnetic Induction at Least Ampere-turns per Centimeter		
			25	50	100
Stg. 38.81	54	20	.....	.....	.....
Stg. 38.81D	54	20	14 500	16 000	17 500
Stg. 45.81	64	16	.....	.....	.....
Stg. 45.81B	64	16	14 500	16 000	17 500
Stg. 50.81R	71	16	.....	.....	.....
Stg. 52.81	74	12	.....	.....	.....
Stg. 60.81	85	8	.....	.....	.....

indicate the quality of the steel used. This can be readily understood when it is considered that the metal in the large casting cools and crystallizes under far different conditions than that in the small test bars.

The standard DIN 1681 does not specify the analysis. It is left to the producer to make the steel to fill the requirements.

American Standards for Steel Castings.—A comparison of German and American standards is of interest. Americans differentiate between a class A without specified strength, but of a certain chemical composition, unannealed, and a class B with special properties, classified into groups:

TABLE XV.—AMERICAN STANDARDS FOR STEEL CASTINGS

	Strength At Least 1000 Lb. per Sq. In.	Elongation: Gage Length 4 × Diam. At Least, Per Cent	Reduction, Per Cent	Bending Test Specimen $\frac{1}{2} \times 2$ In. Angle
Soft.....	60	24	35	120°
Medium.....	70	20	30	90°
Hard.....	80	17	25	.....

In special cases, where the simple annealing does not produce the required strength, the castings are rapidly cooled and then

annealed at a temperature just below the transformation range, 650° C. (1200° F.). This treatment cannot always be recommended for cast straight carbon steel because of the danger of cracking during the rapid cooling. However, if a cast alloy steel is used it can be given a mild hardening treatment in oil and then annealed. Lorenz¹ gives an example, presented in Table XVI,

TABLE XVI.—RESULT OF HARDENING AND ANNEALING CAST ALLOY STEEL
(By Lorenz)

	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Reduction, Per Cent
Annealed.....	60	100	15	20
Heat treated.....	100	114	15-20	30-50

showing the effect of this treatment on a cast alloy steel of the following composition: 0.40% C, 1.5 to 2.0% Ni, 0.6 to 0.8% Cr. Cast gears have been successfully case hardened.

Forged Steel Castings.—A combination of casting and forging whereby the casting is pressed into a die to obtain exact dimensions is used in America. The parts made by this method are not of as good quality as those made by the straight forging process, since they lack the thorough working given by the latter process. The process of rolling and forging closes voids and blow-holes much better than the process of pressing the casting by a single operation in a die.

The use of alloy steel castings has a promising future, particularly in the automobile industry. Because of the low density of the castings, they cannot be advantageously used for highly stressed gears, but in such cases as connecting rods, etc., they will give good service provided the increased weight is not a disadvantage.

The use of over-forged cast steel depends on relative cost considerations and is possible only in quantity production, where the molding is economical. In this case the process is so much cheaper than drop forging that Ford, for instance, makes a considerable number of parts by this method.

¹ *Stahl u. Eisen*, 43 (1923), p. 105.

2. CASE-HARDENING STEELS

Effect of Case-hardening.—Some parts must be tough and at the same time have high resistance to wear. This requirement led to the development of the case-hardening process, a method by which soft steel is given a high carbon content, up to about 1%, at and near the surface. When this steel is heated and quenched the outside will become very hard while the low carbon interior will remain soft and tough. The steels used for case-hardening are low in carbon, usually containing not much more than 0.15%, but sometimes up to 0.2%. Alloy steels are rapidly replacing the straight carbon type for case-hardening work. The use of alloy steels with their higher physical properties permits the use of smaller sections and therefore results in lower weight. The alloy additions, especially of chromium and nickel, do not affect the hardness of the case, but change the properties of the core in two ways. In the first place they increase the strength, even of the annealed material, without reducing the toughness, and in the second place they result in deeper hardening on quenching by reducing the critical cooling velocity.

Case-hardening is done by first packing the pieces in a substance which contains carbon, and then heating to 900° C. (1650° F.), at which temperature the steel is able to absorb carbon. The temperature and time are regulated so that the carbon content will not exceed about 0.9% at the surface and so that at a depth of about $\frac{1}{16}$ in. the carbon content is that of the original steel (0.1%). When the carburized pieces are then heated to the proper temperature and quenched, the outside will become glass-hard, while the core, although hardened to a slight extent, still remains comparatively soft and tough on account of the low carbon content. The part will thus have a glass-hard surface and a tough core, the hard surface offering resistance to wear, and the tough core reducing the danger of breakage.

The Test of Surface Hardening.—In testing case-hardened steel it is desired to find whether the surface is sufficiently hard and whether the core has the required strength. The surface hardness can be determined roughly with a file, the file should not stick or should stick only slightly when drawn across the piece. This method gives the desired information very quickly when used by an expert, but does not give a numerical measure-

ment of the hardness. The "Werkstoffausschuss des Vereins deutscher Eisenhüttenleute" has made wide investigations¹ on the hardness testing of case-hardened steels with the following results which are based on the assumption that a certain depth is reached and that the carbon on the outside is 0.9%:

"The Brinell test with 10-mm. ball and 3000-kg. load is not suitable for testing case-hardened pieces. When the hardened depth is 1 mm. or over, hardness tests can be made using the 5-mm. ball and 750-kg. load. The Shore scleroscope gives wide variations with different instruments, but can be used when the depth of hardness is $\frac{1}{32}$ in. or over and the stock is $1\frac{1}{2}$ in. thick or over, providing the same instrument is used for all tests. The Rockwell hardness tester gives very good results on a hardened depth of 1 mm. or over, and is very simple to use. It employs the same principle as the Brinell test, but uses a diamond cone penetrator and a 150-kg. load."

The Test of Core Toughness.—The properties of the core cannot be obtained after case-hardening because the influence of the case cannot be eliminated. To get at the properties of the core of the case-hardened steel, a piece is packed in sand and treated just the same as though it were to be case-carburized and hardened. Then tensile and notch test bars are cut and tested. The diameter section of the original piece is important and should be about $1\frac{1}{4}$ to $1\frac{1}{2}$ in. square. If the section is too large the effect of quenching will not reach the core, and if too small the piece will be hardened throughout and the strength obtained will be too high. Test pieces for this purpose have not yet been standardized.

Sometimes test bars are cut from the bars of case-hardening material, turned to size, and then hardened and tested. This gives wrong values because the test piece was not subjected to the long heating of the case-hardening process, and besides, owing to its small sections, will be hardened throughout and therefore have too high a strength. The piece to be hardened should be heat-treated before the test bars are cut from them. This can be easily done except in the case of high chromium-nickel steels, for instance 4% nickel and 1% chromium, which have very high strength after hardening (185 000 lb. per sq. in.) and are nearly impossible to machine. Such steels can be turned to size before

¹ Bericht, Nr. 97.

hardening, then enclosed in a tightly fitting shell of the same outside diameter as the original piece, and hardened. Even this method is objectionable because of the difficulty of maintaining close contact between the test bar and the outer shell during heating. The test bars of this material can not be made too large since the standard testing machines can not break pieces of it that are more than about $\frac{3}{4}$ in. in diameter. Tests for toughness are best made as notched bar tests.

The hard outside layer of case-hardened steel offers protection against notching effects and fatigue breaks. Case-hardened test pieces have given, in fatigue tests, repetitions of 10 million blows and more, the values being somewhat independent of the other properties and the composition.

The Straight Carbon Case-hardening Steels.—The straight carbon case-hardening steels usually have the following composition:

Carbon.....	0.05 to 0.20%
Manganese.....	0.30 to 0.50%
Silicon.....	0.15 to 0.30%
Phosphorus.....	max. 0.05%
Sulphur.....	max. 0.04% ¹

The core has the following properties:

Yield point.....	35 500 to 71 000 lb. per sq. in.
Elongation.....	10 to 20%
Strength.....	57 000 to 128 000 lb. per sq. in.
Reduction.....	50 to 65% ¹

The general properties of the case-hardening steels are compiled in Table XVII. These steels are used for cam shafts, bolts, spring pins, gears, levers, transmission gears of light cars, chain pins, rolls, shafting for low stresses, bushings, swivels, sprockets, etc.; in short, for all those parts which are not too highly stressed and which must have a glass-hard surface and a tough core.

Nickel Case-Hardening Steels.—The low strength of straight carbon case-hardening steels led to the addition of various alloying elements for the purpose of increasing the strength without reducing the toughness too much. Nickel was among the first of such elements to be used, and the nickel case-hardening steels are today of considerable importance in automobile construction,

¹ Rapatz, Die Edelstähle, p. 4.

TABLE XVII.—PROPERTIES OF CASE-HARDENED STEELS

Carbon, Per Cent	Manga- nese, Per Cent	Silicon, Per Cent	State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduc- tion, Per Cent	Notch Tough- ness, Ft.-lb. per Sq. In.
						10 × Diam., Per Cent	5 × Diam., Per Cent		
Up to 0.10	About 0.45	About 0.15	Annealed	25-34	50- 59	30-33	38-45	70-75	1400
			Hardened in oil...	35-50	60- 68	20-25	24-30	60-70	1400
			Hardened in water	45-57	64- 71	14-20	20-26	60-70	1170-1400
0.10- 0.15	0.40- 0.50	0.15- 0.20	Annealed	28-43	54- 64	28-30	34-38	65-70	1400
			Hardened in oil...	43-57	71- 85	16-20	20-26	55-65	1170
			Hardened in water	43-71	71-100	16-20	20-24	55-65	970-1170
0.15- 0.18	0.60- 0.80	0.20- 0.30	Annealed	37-45	54- 67	24-30	30-33	60-70	1400
			Hardened in oil...	43-64	78-100	12-18	16-22	50-60	1170
			Hardened in water	64-71	85-128	10-10	12-18	50-60	930-1170

although they are being replaced by the chromium-nickel steels. The composition of nickel steel is about as follows: C 0.05 to 0.20%, Mn about 0.50%, Si 0.20 to 0.30%, P max. 0.045%; S. max. 0.04%, Ni 1.0 to 8.0%. The properties of the core vary within the following limits:

Yield point.....	42 700 to 100 000 lb. per sq. in.
Elongation.....	12 to 20%
Strength.....	57 000 to 142 000 lb. per sq. in.
Reduction.....	50 to 65% ¹

Considerable hardness is obtained with as little as 2% nickel, and at 6% nickel the carburized outer zone is martensitic and almost file-hard even on slow cooling. Although these higher nickel steels would not require the final hardening process with the accompanying danger of warping, they are seldom used. The most common of the nickel case-hardening steels are those containing between 2% and 3% of nickel. Rapatz¹ gives the values for nickel steel shown in Table XVIII.

¹ F. Rapatz, Die Edelstähle, p. 4.

TABLE XVIII.—PROPERTIES OF NICKEL CASE-HARDENING STEELS

(By Rapatz)

Carbon, Per Cent	Nickel, Per Cent	State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Reduction, Per Cent	Range of Use
0.05-0.15	1.0-2.0	annealed	36-43	57- 64	25-30	60-70	Pipes
		hardened	71-85	100-114	10-15	40-45	Sheet metal rivets
0.05-0.15	2.5-3.5	annealed	40-43	64- 78	22-25	55-60	Gears
		hardened	.....	114-128	10-14	30-40	Sprockets, camshafts
0.05-0.15	4.0-6.0	annealed	50-64	78- 93	20-25	45-55	Shafts
		hardened	.....	128-142	.....	.....	Bolts

Chromium Case-hardening Steels.—Among American automobile manufacturers chromium case-hardening steels are quite important, but in Germany they cannot compete with the chromium-nickel steels. The chromium content of these steels is usually between 0.5 and 1.0%. A steel with 0.15% C, 0.4 to 0.5% Mn, 0.2 to 0.3% Si, max. 0.045% P, 0.04% S, 0.5 to 1% Cr, had the properties given in Table XIX.

TABLE XIX.—PROPERTIES OF CHROMIUM CASE-HARDENING STEELS

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Annealed.....	42.7-51	64- 85	15-20	20-30	60-70
Hardened.....	93-107	114-142	7-12	10-15	30-40

Chromium case-hardening steels are comparatively low priced, but are not popular because of their short fiber. They also cause much trouble by giving soft spots in case-hardening. They are used for rolls and roller bearings in the following composition:

	Carbon, Per Cent	Chromium, Per Cent ¹
For roller bearings...	0.15 to 0.20	1.0 to 2.0
For rollers.....	0.15 to 0.20	0.4 to 0.6

¹ F. Rapatz, Die Edelmähle, p. 108.

It is evident that the surface of this steel, when carburized, corresponds to a common 1% carbon, 1.5% chromium steel.

Chromium-nickel Case-hardening Steels.—The outstanding alloy case-hardening steels are the chromium-nickel type. They have the advantage over the plain nickel steels that they harden through even in large sections, and also that they have higher strength for the same toughness. Rapatz¹ gives the data in Table XX.

TABLE XX.—PROPERTIES OF CHROMIUM-NICKEL CASE-HARDENING STEELS
(By Rapatz)

Car- bon	Chro- mium	Nickel	State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elong- ation, Per Cent	Re- duc- tion, Per Cent	Used for
Up to 0.20	0.6-0.9	3.0-3.5	annealed hardened	64- 71 128-157	85-100 171-200	20-25 8-12	60-65 30-40	Gears Rollers Spindles
0.20	0.6-1.0	4.0-4.5	annealed hardened	71- 78 142-192	93-114 185-228	12-20 5-10	50-60 25-35	
0.18	0.85-1.8	4.5-5.0	annealed hardened	78-100 171-250	107-142 214-284	10-18 5-10	45-60 30-40	

For gears, sprockets, camshafts, trunnions, bolts, and other highly stressed case-hardened parts, the steel mentioned in Table XXI is used. The higher the nickel content of these steels, the better they retain their toughness even with high strength. The values found in testing the higher strength steels show large variations because the procedure of the test has considerable influence on the results. Notch test pieces can not be hardened with sufficient uniformity; therefore results for these tests are omitted. For a good chromium-nickel steel they will be around 930 to 1400 ft.-lb. per sq. in. for the hardened piece.

¹ F. Rapatz, *Die Edelstähle*, p. 117.

TABLE XXI.—CHROMIUM-NICKEL CASE-HARDENING STEEL

Carbon	Manga- nese	Chromium	Nickel	Annealed				
				Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduc- tion, Per Cent
						10 × Diam., Per Cent	5 × Diam., Per Cent	
0.10-0.15	0.50	0.45-0.55	1.0-1.5	43- 57	57- 71	22-25	30-35	65-75
0.10-0.15	0.50	0.45-0.55	2.0-2.5	43- 57	64- 78	21-25	28-35	65-75
0.10-0.15	0.50	0.70-0.90	2.5-3.0	50- 64	78- 92	18-23	25-30	65-75
0.10-0.15	0.50	0.30-0.50	2.7-3.3	50- 64	71- 86	20-26	26-32	65-75
0.10-0.15	0.50	0.50-0.70	2.7-3.3	57- 71	78- 92	20-25	23-30	60-70
0.10-0.15	0.50	0.70-0.90	2.7-3.3	64- 78	78- 92	18-23	22-28	60-70
0.10-0.15	0.50	0.60-0.80	3.3-3.8	64- 85	85-100	18-21	22-26	60-70
0.10-0.15	0.50	0.60-0.80	3.8-4.2	64- 85	85-100	16-20	21-25	60-70
0.10-0.15	0.50	0.80-1.00	3.8-4.2	71- 85	93-107	16-19	20-25	55-65
0.10-0.15	0.50	1.00-1.20	3.8-4.2	71- 93	93-107	14-18	18-24	50-60
0.10-0.15	0.50	0.80-1.10	4.2-4.8	78- 93	93-107	15-18	20-24	50-60
0.10-0.15	0.50	1.10-1.40	4.2-4.8	85-100	100-114	12-18	15-22	50-60

Carbon	Manga- nese	Chromium	Nickel	Hardened in Oil				
				Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduc- tion, Per Cent
						10 × Diam., Per Cent	5 × Diam., Per Cent	
0.10-0.15	0.50	0.45-0.55	1.0-1.5	85-114	100-135	10-16	13-20	55-65
0.10-0.15	0.50	0.45-0.55	2.0-2.5	100-114	128-150	8-14	10-17	50-65
0.10-0.15	0.50	0.70-0.90	2.5-3.0	121-142	135-164	8-10	10-14	50-60
0.10-0.15	0.50	0.30-0.50	2.7-3.3	100-128	128-157	9-11	10-15	50-60
0.10-0.15	0.50	0.50-0.70	2.7-3.3	135-150	142-164	7-10	10-14	40-60
0.10-0.15	0.50	0.70-0.90	2.7-3.3	135-157	150-171	7- 9	10-14	40-60
0.10-0.15	0.50	0.60-0.80	3.3-3.8	128-157	150-178	7- 9	10-14	40-60
0.10-0.15	0.50	0.60-0.80	3.8-4.2	128-157	157-185	7- 9	10-13	40-60
0.10-0.15	0.50	0.80-1.00	3.8-4.2	142-171	171-185	7- 9	10-14	45-55
0.10-0.15	0.50	1.00-1.20	3.8-4.2	150-185	185-200	6- 9	8-13	40-55
0.10-0.15	0.50	0.80-1.10	4.2-4.8	142-185	171-200	7-10	9-15	40-65
0.10-0.15	0.50	1.10-1.40	4.2-4.8	171-214	200-242	6- 8	8-11	40-50

Carbon	Manga- nese	Chromium	Nickel	Hardened in Water				
				Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduc- tion, Per Cent
						10 × Diam., Per Cent	5 × Diam., Per Cent	
0.10-0.15	0.50	0.45-0.55	1.0-1.5	121-128	128-150	8-12	10-15	40-50
0.10-0.15	0.50	0.45-0.55	2.0-2.5	121-135	142-164	7-12	9-14	40-50
0.10-0.15	0.50	0.70-0.90	2.5-3.0	135-157	157-178	6- 9	7-12	30-40
0.10-0.15	0.50	0.30-0.50	2.7-3.3	107-135	150-164	7-10	9-13	40-50
0.10-0.15	0.50	0.50-0.70	2.7-3.3	142-157	157-178	6- 9	9-12	40-50
0.10-0.15	0.50	0.70-0.90	2.7-3.3	150-171	164-185	6- 9	9-12	40-50
0.10-0.15	0.50	0.60-0.80	3.3-3.8	150-178	171-192	5- 8	8-12	40-50
0.10-0.15	0.50	0.60-0.80	3.8-4.2	150-178	178-200	5- 8	8-12	40-50
0.10-0.15	0.50	0.80-1.00	3.8-4.2	157-185	185-200	5- 8	8-12	40-50
0.10-0.15	0.50	1.00-1.20	3.8-4.2	164-192	200-214	5- 7	7-10	30-40
0.10-0.15	0.50	0.80-1.10	4.2-4.8	157-200	185-228	6- 8	7-13	40-55
0.10-0.15	0.50	1.10-1.40	4.2-4.8	200-228	228-256	5- 7	7- 9	35-45

3. CASE-HARDENING PROCESS

Preparation of Parts for Case-hardening.—The case-hardening operation itself may completely ruin even the best steel if not carried out properly. The parts to be carburized must be machined to size and finish-ground. The surface must be free from rust if the carburization is to be uniform and if soft spots are to be avoided. When it is desired to prevent certain parts of the work from being carburized, this can be done in several ways. Perhaps the most common is to paste these parts over with clay or asbestos, which should be allowed to dry a little before the heating in order to avoid cracking. Another method is to electroplate the parts to be protected, but this process is not used much as yet in Germany. The method is a little complicated but gives a clean job. The pieces must first be cleaned thoroughly of all grease, which is done by immersion in a 15 to 20% solution of potash; they are then washed in boiling water and dried in sawdust. The parts that are not to be plated are coated with a mixture of beeswax and rosin. The parts to be plated, which may have taken up a little of the grease, are again cleaned, which may be done electrolytically in a soda-lye solution. The pieces, thus prepared, are dipped in a solution of copper sulphate in which a copper deposition is formed within thirty minutes. Guillet's¹ report on the protective effect of copper coating is given by Table XXII.

TABLE XXII.—RESULTS SHOWING EFFECT OF COPPER COATING

(By Guillet)

Case-hardening Temperature		Case of Unprotected Region, Depth, In.	Copper Coat, In.	Effect of Protective Coating
Deg. C.	Deg. F.			
1000	1830	0.0394–0.433	0.0004–0.0008	Slight cementation
1000	1830	0.0394–0.433	0.0008–0.0012	Complete protection
1000	1830	0.0707–0.787	0.0004–0.0008	Strong cementation
1000	1830	0.0707–0.787	0.0012–0.0016	Complete protection
850	1560	0.0394–0.433	0.0004–0.0008	Complete protection

¹ *Génie civil* (1922), pp. 273, 292, 315, 337; *Stahl u. Eisen*, 44 (1924), p. 663.

Another method of keeping part of the pieces soft, which may occasionally be used, is to leave these places about $\frac{1}{16}$ in. oversize when the piece is machined. Then after carburizing, but before hardening, when the surface is still soft, these oversize places can be machined off, thus removing most of the absorbed carbon.

The Carburizers.—Carburizing material can be purchased ready for use. A mixture which works very well is one composed of 60% charcoal and 40% barium carbonate. The latter substance decomposes when heated, giving carbon dioxide which is reduced to carbon monoxide by the carbon present. The carbon monoxide is most effective in doing the carburizing. The actual mechanism of the carburizing process has not yet been completely determined, but it has been established that carbonaceous gases are mainly responsible.

The following data concerning the effects and properties of the various carburizing substances have been given by H. B. Knowlton;¹

- a. Charcoal. Usually used in mixture. If used alone the action is slow and there is danger of soft spots. The substance loses much of its effectiveness in use.
- b. Leather charcoal. Gives rapid carburizing and high carbon content on the surface. Large addition of fresh material must be made each time it is used.
- c. Bone charcoal. Carburizes rapidly. 50% of fresh material must be added each time it is used.
- d. Coal and coke. Not very effective; works a little better if mixed with oil.
- e. Potassium cyanide. Always speeds up process and gives hard surface.
- f. Carbonates. Decompose giving carbon dioxide (CO_2) which reduced to carbon monoxide (CO) results in rapid carburizing. Inexpensive to regenerate since they take up CO_2 from the air.
- g. Various additions such as salt, glass, and sand, whose exact effect has not been determined. Salt aids considerably the carburizing effect of charcoal, but it must be protected from moisture, otherwise it starts corrosion.

The substances named are the main constituents of carburizers and can generally be obtained ready for use.

Since the carburizing action is due largely to gases produced from the carburizer by heating, the gas productivity of the sub-

¹ H. B. Knowlton, *Forging and Heat Treating* (1921), Dec., p. 530; *Stahl u. Eisen*, 42 (1922), p. 822.

stance is important. It is also important that the evolution of gas does not start before the carburizing temperature of the steel is reached.

In judging carburizing substances the following points should be considered:¹

1. Velocity of carburizing at various temperatures.
2. Repeated use without exhaustion.
3. Low specific weight. Carburizers are sold by weight and used by volume.
4. Low shrinkage in use. Small constant shrinkage is better than a large shrinkage at the start.
5. Freedom from substances that might attack the steel.
6. Freedom from dust.
7. Good thermal conductivity.

Carburizing Boxes.—The parts to be carburized are packed, together with the carburizer, in boxes or pipes. The boxes should be tight enough so that the carburizing gases can not escape and so that the steel will not oxidize. Also they should not warp. If there are openings in the boxes, scale may fall on the pieces, resulting in soft spots.

It is good policy not to try to economize when buying carburizing boxes. The higher price of good alloy boxes will be more than offset by their longer life. The following figures give a comparison of the durability of various types of boxes in service:

Cast-iron boxes.....	200 to 300 hours
Cast or forged steel.....	700 to 1,000 hours
Chromium nickel steel.....	3,000 to 5,000 hours

The boxes should, if possible, be made to fit the form and size of the parts to be carburized. The parts are completely covered with carburizer to a depth of an inch or so, and very firmly tamped in, so as to prevent the carburizer from falling away from the work with resulting soft spots. On account of the danger of the carburizer's shrinking away from the parts, it is better to use a slowly

¹ B. F. Shephard, A.S.S.T. Handbook, Carburizing and Heat Treating of Carbon Steels, R3-R13.

combustible carburizer, which requires a longer time for carburizing than a rapidly combustible one that may carburize more quickly but is apt to shrink. A more uniform depth of carburizing will be obtained if several small boxes are used for the individual parts rather than putting a lot of them in one large box. Pieces of iron are sometimes mixed with the carburizer to improve the thermal conductivity.

When the boxes are completely filled, their covers are luted on with clay and they are put into the furnace. The carburizing temperature for straight carbon steel is 850 to 900° C. (1560 to 1650° F.); and for alloy steels is 820 to 850° C. (1510 to 1560° F.). The time varies, according to the size of the box and the desired depth of carburizing, from two to six hours. The desirable depth of carburizing for different sections is as follows:

1½-in. wall.	0.04–0.05 in. depth of case
¾-in. wall.	0.03–0.04 in. depth of case
⅜-in. wall.	0.02 in. depth of case

Carburizing Temperature and Time.—It is very important that the proper carburizing temperature shall be maintained. A higher temperature increases the rate of carburizing, but it tends to produce warping and also is apt to give uneven carburizing. A high carburizing temperature also results in too high a carbon content in the outer zone, which is undesirable and makes the transition from the carburized case to the core very abrupt. However, it is possible to carburize to 1.15% carbon at the outside if the surface is later ground down until the 0.9% carbon zone is reached. When fast and cheap carburizing is required and high quality is not such an important factor, the carburizing temperature may be increased from the usual 850 to 900° C. (1560 to 1650° F.) to be 940 to 960° C. (1725 to 1760° F.). If only a thin carburized layer is required greater uniformity is obtained by keeping the temperature down to 820 to 840° C. (1510 to 1545° F.). Sometimes parts are hardened without reheating after carburizing and in this case the carburizing temperature should be 50° C. (120° F.) less to avoid a coarse grain structure.

The progress of the carburization may be observed by means of test pieces of ⅜-in. diameter which are packed in the boxes,

removed from time to time as the heating proceeds, and broken. If the test piece shows that the desired depth has been reached, the boxes are removed from the furnace.

Double-Hardening Treatment.—The parts after carburizing are hardened, and it is also necessary to refine the grain size, which has become very large due to the long heating. If the carbon content at the outside is above 0.9%, then on slow cooling cementite will separate out at the grain boundaries, making the surface layer brittle and liable to chip off. To avoid this difficulty, it is necessary to harden the pieces at a temperature at which the cementite is still in solution. F. Brüsewitz¹ has developed a process which is largely used today, and probably gives the best results. The parts after being removed from the carburizing boxes are quenched in oil while they are still at a red heat, then annealed in oil at 600° C. (1110° F.) for an hour, and finally quenched from 765 to 800° C. (1410 to 1470° F.) in water or oil according to the form and size of the piece. Where the stresses to be encountered are not large, it will be sufficient to give the pieces only one intermediate anneal, for the straight carbon steel at 650 to 700° C. (1200 to 1290° F.) and for alloy steels at 600 to 650° C. (1110 to 1200° F.), followed immediately by the finish quenching. Very good grain refinement is also obtained by a double-hardening treatment omitting the intermediate annealing step, described above. All these methods give good results if the proper temperatures are used, and it is best to follow exactly the instructions given by the steel maker.

Baths for Case-hardening.—In the quantity case-hardening of small parts it is advantageous to use a salt bath. The baths used for this work consist principally of melted potassium cyanide with additions of sodium and potassium chlorides. The parts are dipped in the melted salts, which are kept at a temperature of 800 to 900° C. (1470 to 1650° F.), for one or two hours and are then removed and usually quenched in water. This treatment gives a surface of extreme hardness, part of which is apparently due to the presence of a certain amount of nitrogen in the outer zone. Shephard² gives data on the properties of the outer zone as presented in Table XXIII.

¹ *Stahl u. Eisen*, 44 (1924), p. 1697.

² *Trans. Am. Soc. Steel Treating*, 1924.

TABLE XXIII.—CARBON CONTENT OF OUTER ZONE IN CASE-HARDENING
(By Shephard)

Case-hardening Temperature		Time, Hours	Depth of Case, In.	Carbon, Per Cent	Nickel, Per Cent
Deg. C.	Deg. F.				
800	1470	15	0.0020	0.35	
800	1470	3	0.0024	0.80	0.38
900	1650	25	0.0016	1.50	0.09

In the "Technische Blätter" of March 5, 1927, the following data are given for a bath consisting of sodium cyanide, sodium chloride, and soda:

Sodium cyanide.....	27%	78%	98%
At a temperature of.....	800° C. 1470° F.	780° C. 1440° F.	750° C. 1380° F.
After, Minutes	The Depth, in Inches, of the Case is		
5	0.0098	0.0098	0.0138
20	0.0236	0.0256	0.0293
50	0.0591	0.0532	0.0551
100	0.0846	0.0826	0.0689
150	0.1023	0.1023	0.0807
180	0.1102	0.1201	0.0964

Since baths containing cyanides are poisonous, the calcium cyanamid process is preferred. In this process the parts are dipped in molten calcium cyanamid.

Powdering with yellow prussiate of potash to obtain a local hardening of the surface is not done in commercial work. Hardening with a torch is only done in repair work and in special cases. In this method, the part to be hardened is heated very rapidly with a torch and then is hardened by the cooling resulting from the rapid absorption of heat by the surrounding metal. The process requires considerable experience and is not suited to general use.

Gas carburization is not extensively used, due probably to the longer time required.

Straightening of Parts.—When the carburized parts have been finally hardened, they are straightened and ground to size. A

disadvantage of the case-hardening process is that considerable warping is apt to occur and can be prevented only by the use of special devices. The grinding operation requires much caution in order to avoid spoiling the hard surface by local heating. Straightening, especially of small sections, can be facilitated by tempering the finished part. In order to avoid damage to the case-hardened zone the temperature should not exceed 200° C. (390° F.), and the piece should by no means be heated beyond the yellow temper color.

Failures in Case-hardening.—Because of the rather complicated nature of the case-hardening process it is necessary to exercise great care if mistakes are to be avoided. Poor results are seldom due to poor quality steel, but rather frequently to the use of an unsuitable steel. If the carbon content is too high, the core will not be tough enough. Manganese content should be below 0.5% because as little as 0.6% may cause brittleness. Lower silicon than 0.10% indicates insufficient deoxidation. Oxides and slag particles are very undesirable in steel for case-hardening, since oxides cause irregular carburizing resulting in uneven depth and soft spots, and slag particles often result in chipping of the outer zone, while straightening.

Complaints regarding the carburized zone are usually the result of incorrect case-hardening. The following things may happen:

The case-hardened surface may show too much wear. The depth of case may not be great enough, as the result of too short a time, too low a temperature, worn-out carburizer or grinding off too much of the outside. In all these cases the fracture exhibits too small a case or none at all. It is also possible that the parts during the intermediate annealing, or before hardening, have been heated too long in an oxidizing atmosphere. Under such conditions a decarburization may occur as in the case of tool steels. If the outer zone is decarburized, then it offers little resistance to wear. If the pieces were heated in a salt bath and quenched in oil, there may have been a crust of salt on parts of the surface which prevents hardening and thus gives soft spots.

If the carburized layer chips off, the rupture will usually show that this layer has been overheated. Instead of the usually fine grain structure the carburized layer has large sparkling grains. Too high a temperature and too long a time of heating during carburizing will also give a carburized layer too high in carbon, and it will chip off due to the presence of cementite needles. If

the chipping occurs in only one or a few places, for instance, on one tooth of a gear, the cause is probably slag particles.

Hardening results in severe internal strains which will cause deformation. Even when the pieces are held in special jigs during hardening, warping will not be entirely avoided. Small deformation may be corrected by grinding, but for larger deformation or where grinding is not feasible the part must be straightened. This is very difficult to do and requires much experience and great care. It will help if the part is tempered slightly but care is required and the temperature should not exceed 200° C. (390° F.).

Shephard has listed the various faults, together with their causes, indication and remedies, as given in Table XXIV.

TABLE XXIV.—GENERAL CASE-HARDENING FAULTS AND REMEDIES
(By Shephard)

Faulty	Cause	Indications Showing Fault	Remedy
Depth and carbon content too great or too small	(1) Wrong temperature.		
	(2) Uneven temperature in furnace or box	Deviation between testpieces from same furnace or box	Change in furnace. Slow and more even heating
	(3) Wrong temperature readings	All boxes are bad	New calibration of pyrometer
	(4) Carburizer too strong or too weak	Parts not carburized as usual	Try new carburizer and change temperature and time of carburization
Soft spots. . . .	(1) Unequal and incorrect temperature	File test	
	(2) Unsuitable means for quenching	File test	More rapid quenching
	(3) Decarburized surface	File test	Follow exact instructions
	(4) Low or uneven carbon content	May occur in carburizing-box or in hardening	Try new carburizer. Test pyrometer
Poor fracture. .	(1) Temperature too high	Break test	Lower hardening temperature
	(2) Carbon too high in outer zone	Break test	Lower temperature. Double hardening with high temperature for first hardening

Nitriding.—The greatest disadvantage of the ordinary case-hardening process is the warping of the parts. Krupp, in Germany, makes parts with high surface hardness which do not have this fault. The process used was developed by Ad. Fry¹ and is known as nitriding. The parts, which are best made from a chromium steel, are first annealed at 600° C. (1110° F.) so as to be absolutely free from strains and then heated in ammonia at a temperature which is usually 500° C. (930° F.) and in no case above 580° C. (1075° F.). The outside becomes very hard, even with slow cooling which avoids warping. A greater surface hardness is obtained by this process than by any other, and it is possible to cut glass with the edge of a piece thus treated. The nitriding of a part results in an increase in thickness which varies from 0.00004 to 0.00008 in. This growth can be controlled closely enough so that it is possible to finish to the final dimensions before hardening and thus to eliminate the final grinding. In America the nitriding process is used by the Westinghouse Electric Company as described in an article in *Machinery*, by T. L. Helquist.²

The nitriding process, although very promising, has its disadvantages. In the first place, the very high surface hardness and its accompanying brittleness are not desirable. To avoid the breaking off of the surface it is necessary to have very well rounded corners, and the pressure per square inch should not exceed 65 000 to 100 000 lb. per sq. in.³ This pressure is about half that used for common case-hardened parts. Another disadvantage is that, owing to the low temperature used and the slow rate of cooling the strengthening influence of the alloy constituents can not be fully utilized.

High-alloy Nickel Steel for Case-hardening.—A possible method of obtaining surface hardness without warping which is already known but which has not been developed into a commercial process, is the use of a 6% nickel, 0.5 to 1.0% chromium steel for case-carburizing. Such a steel containing 1% carbon is self-hardening when cooled slowly from 800° C. (1470° F.) and if parts are made from low carbon steel of this alloy composition and case-carburized, they may be hardened on the surface by slow cooling. The slow cooling avoids warping and internal cooling

¹ *Stahl u. Eisen*, 43 (1923), 1271.

² The Nitriding Process and Its Advantages, *Machinery*, May 1929, p. 647.

³ Ad. Fry, *Auto-Technik* (1925), H. 20, p. 27.

stresses. This type of steel gives some difficulty in forging, and it is probably for this reason that it has not been used to a greater extent.

4. THE HEAT-TREATING STEELS

The Nature of Heat Treatment.—Heat treating consists of hardening, followed by a tempering operation to obtain the necessary toughness. The temperature and duration of tempering determine the final hardness and strength, which are the factors determining the toughness. The relation of these properties is shown in Fig. 42, after Wendt. When steel is hardened it is brittle, has a high strength, and has little toughness. When it is tempered, that is, by heating below 650°C . (1200°F .), it loses in strength and hardness, but becomes much tougher.

The tempering operation therefore sacrifices some of the hardness in order to obtain toughness. Hardening imparts to the steel a fine structure which is not lost on tempering. Thus heat treatment gives the highest qualities that can be obtained with a given steel, since no other process gives as even and fine a structure. Even if the tempering is carried to such a temperature and time that the strength of annealed steel is obtained, the toughness is still superior to that of the annealed steel because of the finer grain size.

The Straight Carbon Heat-treat Steels.—For straight carbon steels, heat treatment does not give as great an improvement in properties. When the section is large, it is not possible to harden

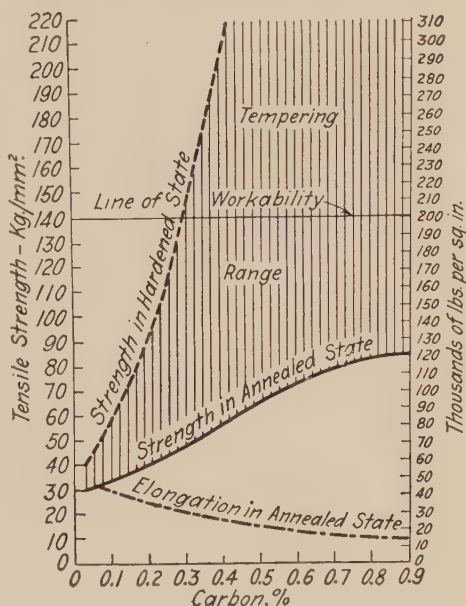


FIG. 42.—Properties of straight carbon steel for various carbon contents.

to the center and therefore the core will not be heat-treated. Even for small pieces the gain resulting from heat treatment is small. In addition carbon steel with high manganese content is apt to show temper brittleness.

Table XXV contains some data on carbon steel in the "as received," "annealed," and "heat treated" states.¹

TABLE XXV.—DATA ON CARBON HEAT-TREAT STEEL

(By Rapatz)

Carbon	Manganese	As Received			Annealed		
		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent
0.4	0.75	57	64	23	58	67	22
0.4	1.50	93	104	14	83	93	18
0.4	1.95	105	118	11	98	102	17
0.6	0.75	102	109	15	84	95	19
0.6	1.50	117	114	12	101	108	14
0.6	1.95	135	145	5	125	131	12

Carbon	Manganese	Heat-treated						
		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Annealing Temperature		Drawing Temperature	
					Deg. C.	Deg. F.	Deg. C.	Deg. F.
0.4	0.75	81	91	17	900	1650	600	1110
0.4	1.50	97	114	13	850	1560	600	1110
0.4	1.95	109	126	12	830	1530	600	1110
.....	.....	154	159	9	880	1616	600	1110
0.6	0.75	135	142	10	900	1650	600	1110
0.6	1.50	161	170	9	850	1560	660	1110
0.6	1.95	170	180	3 *	750	1380	660	1110

* At higher hardening temperature 6 per cent could be obtained.

¹ Rapatz, Die Edelmstähle, p. 84.

The data of Table XXVI are based on the results of a very large number of tests on steel of the usual quality (less than 0.035% phosphorus and 0.035% sulphur). It is of course possible to obtain other properties with these steels by varying the heat treatment, but the ones given are those of the steel as most commonly used.

TABLE XXVI.—DATA ON CARBON HEAT-TREAT STEELS

Carbon	Manga- nese	Annealed				
		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduc- tion, Per Cent
				10× Diam., Per Cent	5× Diam., Per Cent	
0.15-0.25	0.6-0.8	36-43	60- 71	24-30	32-40	65-70
0.25-0.35	0.8-1.0	43-50	71- 78	22-27	28-35	50-60
0.30-0.40	0.6-0.8	43-50	75- 85	20-25	25-30	45-55
0.30-0.40	1.8-2.0	43-57	78- 92	19-24	24-30	45-55
0.35-0.45	1.0-1.2	43-57	78- 92	18-23	22-28	40-50
0.40-0.50	0.6-0.8	50-64	85-100	18-21	22-29	45-60
0.50-0.60	0.6-0.8	57-60	100-107	15-19	19-26	40-50

Carbon	Manga- nese	Heat-treated				
		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduc- tion, Per Cent
				10× Diam., Per Cent	5× Diam., Per Cent	
0.15-0.25	0.6-0.8	50- 64	77- 92	19-24	26-33	70-75
0.25-0.35	0.8-1.0	64- 78	92-107	16-18	21-25	60-70
0.30-0.40	0.6-0.8	64- 78	92-107	15-19	20-26	55-65
0.30-0.40	1.8-2.0	85- 92	102-114	14-17	20-23	55-65
0.35-0.45	1.0-1.2	85-100	114-128	12-17	18-24	50-60
0.40-0.50	0.6-0.8	78- 92	114-128	14-16	19-23	50-60
0.50-0.60	0.6-0.8	85-107	114-128	10-15	15-20	40-50

The Nickel Heat-Treat-Steels.—The effect of heat treatment is most marked when alloy steels are used. Alloy steels in general

have higher properties in the annealed condition than do straight carbon steels, and in addition they harden deeper on quenching. Nickel steels used for heat treating usually have the properties given in Table XXVII.¹

TABLE XXVII.—PROPERTIES OF NICKEL STEELS USED FOR HEAT TREATING
(By Rapatz)

Carbon, Per Cent	Nickel, Per Cent	State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elonga- tion, Per Cent	Reduc- tion, Per Cent
0.2-0.45	1.5-3.5	annealed....	50-57	85-100	14-18	50-60
		heat treated.	50-71	85-107	12-16	50-60
		heat treated.	92-107	107-121	8-12	.....
0.2-0.45	3.0-4.0	annealed....	57-64	100-107	12-16	45-50
		heat treated.	64-78	107-121	8-12	50-60
		heat treated.	92-107	121-136	6-10	.....
0.25-0.45	4.0-6.0	annealed....	64-78	107-121	12-15	45-55
		heat treated.	71-78	121-136	8-12	50-60
		heat treated.	92-107	136-157	6-10	.....

Steels containing 3.5% nickel, or more, have a limited use since they are expensive, and above 5% nickel they are hard to forge and heat-treat. The most commonly used are those with 1.0 to 3.5% nickel, 0.4 to 0.6% manganese, and 0.2 to 0.3% silicon. Table XXVIII contains the results obtained by Barton² on steels containing 3 to 3.5% nickel which were twice quenched and tempered. This process is sometimes used to give the desired fine-grained structure.

Figures 43 and 44 give the properties of the two nickel heat-treat steels most commonly used in America for automobile manufacture.

L. Deville and Ch. Heinen³ report the following values for a nickel steel with 0.20 to 0.30% C, 0.40 to 0.50% Mn, 0.15 to

¹ F. Rapatz, *Die Edelmstähle*, p. 98.

² *Forging, Stamping, Heat Treating*, 1923, p. 102.

³ *Aciers Speciaux et leurs emplois*, Oct., 1925, p. 131-9.

0.25% Si, max. 0.040 S and P, 2.8 to 3.3% Ni. The elongation refers to the French standard gage length $l = 4$ in., $d = 0.543$ in.

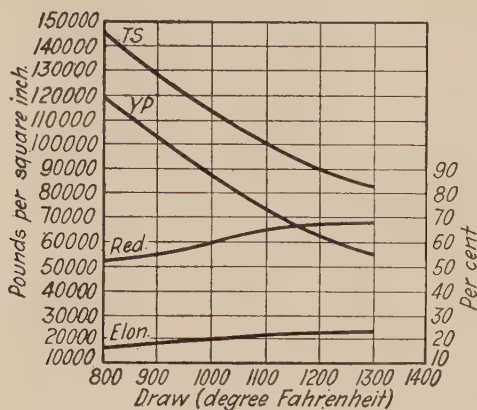


FIG. 43.—Properties of American steel S.A.E. 2330.

The high manganese content of American nickel steels is avoided in Germany, since the results obtained in its use were not

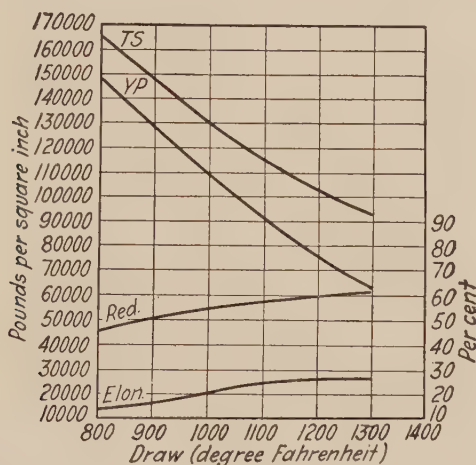


FIG. 44.—Properties of American steel S.A.E. 2340.

very satisfactory. This steel tends to crack and must be handled very carefully in heat treatment. Table XXX gives an idea of the nickel heat-treating steel used in Germany.

TABLE XXVIII.—RESULTS WITH NICKEL STEELS TWICE QUENCHED AND TEMPERED

(By Barton)

Carbon, per Cent	Hardening Temperature				Drawing Temperature		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Reduction, Per Cent
	1		2							
	Deg. C.	Deg. F.	Deg. C.	Deg. F.	Deg. C.	Deg. F.				
0.15	985	1805	845	1550	345	650	70	74	30.0	68.0
	985	1805	845	1550	540	1000	53	74	33.0	72.0
	985	1805	845	1550	705	1300	50	70	35.0	75.0
0.20	930	1705	815	1500	345	650	119	130	22.5	56.0
	930	1705	815	1500	540	1000	85	115	26.5	65.0
	930	1705	815	1500	705	1300	74	107	28.0	67.5
0.30	875	1605	790	1450	345	650	174	204	13.0	52.5
	875	1605	790	1450	540	1000	125	144	18.5	55.0
	875	1605	790	1450	705	1300	85	100	25.5	60.0
0.40	845	1550	775	1430	345	650	179	199	15.0	45.0
	845	1550	775	1430	540	1000	120	139	20.0	55.0
	845	1550	775	1430	705	1300	90	110	23.0	60.0

TABLE XXIX.—PROPERTIES OF NICKEL HEAT-TREATING STEEL

(By Deville and Heinen)

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. Per Sq. In.	Elongation, Per Cent	Reduction, Per Cent
As delivered.....	57-69	78- 93	20-24	40-50
At 850° C. (1560° F.), hardened in oil and drawn to 650° C. (1200° F.).....	71-86	100-114	17-21	50-60

Nickel steels with 4 to 5% nickel are very rarely used. Steel with lower alloy content is cheaper and serves the same purpose. The main uses for nickel heat-treating steels is for shaftings, axles, steering spindles, connecting rods, levers, cranks, and chassis frames. They are not extensively used, however, since for shaftings they have poorer running qualities than chromium-nickel steels, and because the chromium-nickel steels can be treated to give a much higher strength.

TABLE XXX.—PROPERTIES OF NICKEL HEAT-TREATING STEEL
USED IN GERMANY

Carbon, Per Cent	Manga- nese, Per Cent	Nickel, Per Cent	State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Re- duc- tion, Per Cent
						10 × Diam., Per Cent	5 × Diam., Per Cent	
0.25-0.35	0.5-0.6	1.5-2.5	annealed....	50- 64	71- 85	19-22	24-28	60-70
			heat treated.	64- 78	85-100	18-23	25-30	60-70
			heat treated.	78- 93	100-114	15-19	20-25	60-65
0.25-0.35	0.5-0.6	2.5-3.5	annealed....	57- 71	78- 93	18-23	24-28	60-70
			heat treated.	78- 93	100-114	15-20	20-27	60-70
			heat treated.	93-107	114-128	13-15	19-22	55-65
0.25-0.35	0.5-0.6	4.0-5.0	annealed....	57- 71	78- 93	19-23	25-30	60-70
			heat treated.	78- 93	100-114	16-20	21-27	60-70
			heat treated.	93-107	114-128	13-15	20-23	60-65

The Chromium Heat-treat Steels.—A recent development, which was started mainly in America, has been to use chromium steels to a considerable extent in automobile manufacture. This alloy steel was tried as a possible substitute for the more expensive chromium-nickel steel. In an Austrian steel works the average properties of some chromium steels as given in Table XXXI were found.

TABLE XXXI.—PROPERTIES OF CHROMIUM HEAT-TREAT STEELS

Carbon, Per Cent	Manga- nese, Per Cent	Chro- mium, Per Cent	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elonga- tion, Per Cent Sq. In.	Reduc- tion, Per Cent	Notch Tough- ness, Ft.-lb. per Sq. In.
0.35	0.70	1.50	90-93	112-117	12.5-17.4	55-64	320- 880
0.19	0.92	1.08	82-95	100-112	13.3-14.3	67-71	890-1030

In Table XXXII data given by Rapatz¹ are a valuable supplement to our knowledge of chromium steels.

Most of these steels have no practical application because of their high chromium content. Table XXXII shows the excellent properties of the high chromium steels, but it is also possible to obtain good properties with lower chromium. Barton, with a

¹ F. Rapatz, Die Edelmähle, p. 114.

TABLE XXXII.—DATA ON CHROMIUM HEAT-TREAT STEEL

(By Rapatz)

Carbon, Per Cent	Chro- mium, Per Cent	Annealing Temperature		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length 5 × Diam., Per Cent	Reduc- tion, Per Cent
		Deg. C.	Deg. F.				
0.16	1.00	670	1240	40.4	65	39	77
0.24	1.50	680	1260	56	83	29	72
0.22	2.90	695	1280	69	92	27	74
0.20	4.90	745	1370	65	94	27	72
0.41	3.05	700	1290	78.2	108	27	69
0.38	5.03	725	1340	70	108	27	68
0.52	1.14	675	1250	85	130	20	56
0.47	2.23	685	1265	89.5	123	21	63
0.48	5.95	735	1355	70	108	26	66
0.64	2.27	685	1265	105	131	20	56
0.59	3.73	708	1310	87.5	117	22	63
0.72	0.95	670	1240	94	148	19	47

2% chromium steel,¹ obtained the values given in Table XXXIII. In heat treating a double hardening process was used.

TABLE XXXIII.—DATA ON 2% CHROMIUM HEAT-TREAT STEEL

(By Barton)

Carbon, Per Cent	Hardening Temperature				Drawing Temperature		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elonga- tion, Per Cent	Redu- tion, Per Cent
	1		2							
	Deg. C.	Deg. F.	Deg. C.	Deg. F.	Deg. C.	Deg. F.				
0.25-0.30	790 W	1454	760 W	1400	705	1330	80	90	25.0	60.5
0.25-0.30	790 W	1454	760 W	1400	540	1000	123	134	16.0	50.0
0.25-0.30	790 W	1454	760 W	1400	400	750	150	170	12.0	55.0
0.30-0.40	815 W	1500	790 W	1454	705	1330	90	104	22.0	65.0
0.30-0.40	815 W	1500	790 W	1454	540	1000	139	149	16.0	50.0
0.30-0.40	815 W	1500	790 W	1454	400	750	180	189	10.0	35.0
0.40-0.50	815 O	1500	790 O	1454	705	1330	109	134	20.0	60.0
0.40-0.50	815 O	1500	790 O	1454	540	1000	150	169	14.0	40.0
0.40-0.50	815 O	1500	790 O	1454	400	750	200	220	10.0	30.0
0.55-0.65	800 O	1470	720 O	1330	705	1330	115	129	17.0	55.0
0.55-0.65	800 O	1470	720 O	1330	540	1000	170	179	13.0	20.0
0.55-0.65	800 O	1470	720 O	1330	400	750	190	229	9.0	30.0

W = water; O = oil.

¹ Forging, Stamping, Heat-Treating, 1923, p. 102.

Contrary to American practice, German chromium steels for heat treating are made with 1% chromium or less. Very good results have been obtained with low alloy content and low hardening temperature. The chromium steel of the analysis employed can be substituted for all ordinary chromium nickel steels and is largely used for highly stressed parts such as crankshafts, axles, etc. The analysis of this chromium steel is 0.25 to 0.30% C, 0.35 to 0.65% Mn, 0.20 to 0.30% Si, 0.50 to 0.70% Cr.

TABLE XXXIV.—GERMAN DATA USING STEEL WITH 0.50 TO 0.70% CHROMIUM

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10× Diam., Per Cent	5× Diam., Per Cent	
Annealed.....	64- 93	85-100	15-20	20-25	50-60
Heat treated.....	78-100	100-114	15-19	20-25	60-70
Heat treated.....	100-114	114-128	13-16	17-22	55-65
Heat treated.....	114-128	128-142	11-13	15-21	50-60

For the last three years chromium steels of about the following analysis have been used in Germany: 0.40 to 0.45% C, 0.60 to 0.80% Mn, 0.9 to 1.1% Cr, 0.25% Si. Those steels are usually heat-treated to a high strength, and the properties given in Table XXXV can be reached.

TABLE XXXV.—PROPERTIES OF GERMAN STEEL WITH 0.90 TO 1.1% CHROMIUM
Hardening Temperature 850° (1560° F.) in Oil

Drawing Temperature		Drawing Time, Min.	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent	Notch Toughness, Ft.-lb. per Sq. In.
Deg. C.	Deg. F.				10× Diam., Per Cent	5× Diam., Per Cent		
450	840	20	192-220	206-228	5- 7	9-12	35-50	328-468
500	930	20	178-206	192-214	7- 8	10-13	40-50	328-654
550	1020	20	163-192	178-200	8- 9	12-15	40-55	514-702
600	1110	20	142-171	156-178	9-10	14-16	45-55	608-795
650	1202	20	128-149	142-156	10-12	16-20	50-60	702-936

The Vanadium Heat-treat Steels.—Following American practice, these steels are also alloyed with 0.15 to 0.2% of vanadium, which is said to improve the properties. There are, however, still too few results available to permit proper judging of the effect of the vanadium. The deviations in test results are very high and the influence of variations in test pieces and procedure is quite great. It is quite possible¹ that the better qualities of vanadium steel are partly due to the fact that the steel manufacturer makes these alloys very carefully, since he would not risk adding the expensive vanadium to a questionable melt.²

The Chromium-silicon Spring Steels.—The chromium-silicon steels are low-alloy heat-treat steels. They have for a long time been used for making springs and have been used since before the war for making crankshafts. They have usually the following analysis: 0.40 to 0.45% C, 0.60 to 0.70% Mn, 0.90 to 1.00% Si, 0.90 to 1.1% Cr. A steel of 0.46% C, 0.58% Mn, 0.96% Si, 1.23% Cr had the properties given in Table XXXVI.

TABLE XXXVI.—PROPERTIES OF CHROMIUM-SILICON STEEL

Hardening Temperature 850° C. (1560° F.) in Oil

Drawing Temperature		Time, Min.	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent	Notch Toughness, Ft.-lb. per Sq. In.
Deg. C.	Deg. F.				10× Diam., Per Cent	5× Diam., Per Cent		
450	840	20	214	232	5.2	7.4	20.8	154
500	930	20	206	221	6.2	9.2	33.0	216
550	1020	20	188	198	8.6	12.0	37.5	322
600	1110	20	150	166	9.9	15.4	50.0	364
650	1200	20	131	150	11.5	17.6	58.2	545
650	1200	30	122	141	14.3	21.8	55.0	605
650	1200	50	105	127	13.8	21.2	56.7	768
700	1290	30	90	123	13.0	20.0	57.8	990

¹ Recent additional note of the authors: Vanadium in the small addition as used for automobile steels has no improving influence upon the steel and it is possible to produce steel with as good qualities without vanadium, if it is carefully done.

² Composition of Ferro-Vanadium for Electric Furnace: 46.2% V, 50.3% Fe, 0.1% C, 1% S, 1.3% Al, 0.05% Ca. M. v. Schwarz, Metall u. Legierungs Kunde, Stuttgart, 1929.

Chromium-silicon steels are probably inferior to the plain chromium type, chiefly because of their lower notch toughness. There are, however, too few test results yet available for a final comparison.¹

The Chromium-nickel Heat-treat Steels.—The steels which are most extensively used for heat-treated parts are of the chromium-nickel type. The main reason for their wide use is that because of the chromium they combine high strength and good toughness, even with low nickel, and thus less of the more expensive nickel needs to be used. With a high nickel content they surpass the plain nickel steels considerably, having higher strength and giving deeper hardening in large sections. For crankshafts heat-treated chromium-nickel steel is now used exclusively, since it has less tendency than the plain nickel steel to smear in the bearings. The composition ranges from 0.2 to 0.45% carbon; 0.4 to 0.8% manganese—preferably 0.55%, since it gives good forging qualities without too great difficulty in heat treating; 0.5 to 1.0% chromium—although some alloy steels have only 0.4 to 0.5%, and in special cases 1 to 1.5% is used; and 1 to 6% nickel, usually about 2 to 3.5%. The properties vary within correspondingly wide limits. The following figures give the composition ranges, and the corresponding ranges in properties, for these chromium-nickel steels.

Carbon, Per Cent	Manga- nese, Per Cent	Chro- mium, Per Cent	Nickel, Per Cent	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elonga- tion, Per Cent	Reduc- tion, Per Cent
0.20-0.45	0.4-0.8	0.4-1.5	1-6	57-228	71-256	5-22	30-70

Among the more thorough investigations on chromium-nickel steel, the work of Barton² is outstanding. His steel had 1.5% nickel and 0.6% chromium, with various percentages of carbon as shown in Table XXXVII:

¹ *Recent additional note of the authors:* Thus far this steel has not been used extensively for automobiles.

² *Forging Stamping, Heat-Treating*, 1923, p. 102.

TABLE XXXVII.—INVESTIGATIONS OF CHROMIUM-NICKEL STEEL
(1.5% Ni; 0.6% Cr)

(By Barton)

Carbon, Per Cent	Hardening Temperature				Drawing Temperature		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation Per Cent
	1		2						
	Deg. C.	Deg. F.	Deg. C.	Deg. F.	Deg. C.	Deg. F.			
0.20	825 <i>W</i>	1520	790 <i>O</i>	1455	705	1300	70	90	22.5
	825 <i>W</i>	1520	790 <i>O</i>	1455	540	1005	110	140	14.0
	825 <i>W</i>	1520	790 <i>O</i>	1455	345	650	140	180	9.0
0.30	790 <i>W</i>	1455	760 <i>O</i>	1400	705	1300	80	110	20.0
	790 <i>W</i>	1455	760 <i>O</i>	1400	540	1005	130	150	15.0
	790 <i>W</i>	1455	760 <i>O</i>	1400	345	650	165	195	10.0
0.40	790 <i>W</i>	1455	760 <i>O</i>	1400	705	1300	100	120	17.5
	790 <i>W</i>	1455	760 <i>O</i>	1400	540	1005	124	150	14.0
	790 <i>W</i>	1455	760 <i>O</i>	1400	345	650	200	219	8.5
0.50	775 <i>W</i>	1430	745 <i>O</i>	1375	705	1300	100	115	18.0
	775 <i>W</i>	1430	745 <i>O</i>	1375	540	1005	155	179	15.5
	775 <i>W</i>	1430	745 <i>O</i>	1375	345	650	229	260	10.5

W = water; O = Oil.

Barton also made similar tests on a steel containing 2.75 to 3.0% nickel and 1 to 1.5% chromium, with the results given in Table XXXVIII. Unfortunately the reduction of area results are not given in this table.

Since there are of course a large number of possible chromium-nickel alloy steels, Table XXXIX gives the properties of the main groups only. However it is possible to infer the properties of steels between these groups.

The influence of nickel is such that a steel with the same strength but higher nickel has a greater elongation. The ratio of chromium to nickel is held closely between 1 to 3 and 1 to 4. Chromium above 1.2% in chromium-nickel steels causes considerable difficulty and also makes the steel more expensive and thus should be avoided.

TABLE XXXVIII.—TESTS OF STEEL 2.75-3.0% NICKEL AND
1-1.5% CHROMIUM

(By Barton)

Carbon, Per Cent	Hardening Temperature				Drawing Temperature		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elong- ation, Per Cent
	1		2						
	Deg. C.	Deg. F.	Deg. C.	Deg. F.	Deg. C.	Deg. F.			
0.30	815 <i>W</i>	1480	760 <i>O</i>	1460	705	1300	80	120	18.0
	815 <i>W</i>	1480	760 <i>O</i>	1460	515	960	130	150	12.5
	815 <i>W</i>	1480	760 <i>O</i>	1460	345	650	179	194	7.5
0.40	790 <i>W</i>	1455	745 <i>O</i>	1370	705	1300	105	120	20.0
	790 <i>W</i>	1455	745 <i>O</i>	1370	515	960	130	150	15.0
	790 <i>W</i>	1455	745 <i>O</i>	1370	345	650	199	223	10.0
0.50	800 <i>W</i>	1472	760 <i>O</i>	1460	705	1300	114	135	19.0
	800 <i>W</i>	1472	760 <i>O</i>	1460	515	960	144	169	15.0
	800 <i>W</i>	1472	760 <i>O</i>	1460	345	650	194	224	10.0

W-water; O-oil.

The main field of application of the chromium-nickel steels is about the same as for the plain nickel steels. They have the advantage that they can be heat-treated to give high strength and they also run better in bearings. They are used for axles, crankshafts, bolts, connecting rods, and sometimes for levers.

Heat Treatment for Medium and High Strength.—The superiority of steel with a high alloy content shows up in the greater toughness when the steel is heat-treated to give higher strength. Table XL shows the composition of a group of steels of high alloy content, together with their properties after heat-treating to give a strength of 120 000 lb. per sq. in. and a strength of 142 000 lb. per sq. in. The notch test pieces after heat treating were cooled once in water (*a* in the table) and once in air (*b* in the table). The fatigue test was made in a Krupp machine on pieces with rounded notches. The values obtained show clearly the superiority of the higher alloy steels when heat treated to give high strength. At 120 000 lb. per sq. in. strength the difference is so slight that the use of high alloy steel would not be justified; but

TABLE XXXIX.—PROPERTIES OF CHIEF CHROMIUM-NICKEL ALLOY STEELS

Carbon, Per Cent	Manga- nese, Per Cent	Chro- mium, Per Cent	Nickel, Per Cent	State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Re- duc- tion, Per Cent
							10 × Diam., Per Cent	5 × Diam., Per Cent	
0.25-0.35	0.55	0.5-0.7	1.0-2.0	annealed. . . .	43- 57	71- 85	20-24	24-32	65-75
				heat treated. .	64- 78	85-100	18-24	24-32	65-75
				heat treated. .	85-100	100-114	16-21	22-28	65-75
				heat treated. .	93-107	114-128	12-17	18-24	50-60
0.30-0.45	0.55	0.5-0.7	1.0-2.0	annealed. . . .	64- 78	85-100	15-19	21-28	60-70
				heat treated. .	85-100	100-114	16-20	22-26	65-75
				heat treated. .	93-107	114-128	11-18	17-23	55-65
				heat treated. .	107-121	128-142	11-14	17-20	55-65
0.25-0.35	0.55	0.6-0.8	2.0-3.0	annealed. . . .	50- 64	85-100	15-22	22-30	60-70
				heat treated. .	85-100	100-114	16-21	23-27	65-75
				heat treated. .	93-107	114-128	12-18	18-24	55-65
				heat treated. .	107-121	128-142	12-14	17-21	55-65
0.30-0.40	0.55	0.8-1.1	2.5-3.5	annealed. . . .	64- 85	92-107	15-20	21-24	60-70
				heat treated. .	93-107	114-128	13-18	19-23	55-65
				heat treated. .	114-128	128-142	11-15	18-21	55-65
				heat treated. .	128-142	142-156	10-12	12-18	50-60
0.25-0.35	0.55	0.6-0.9	3.0-4.0	annealed. . . .	64- 85	92-107	16-22	22-28	60-70
				heat treated. .	93-107	114-128	14-19	19-25	60-70
				heat treated. .	114-128	128-142	12-15	18-22	60-70
				heat treated. .	128-142	142-156	10-13	15-18	55-65

after heat-treating to a strength of 140 000 lb. per sq. in. the notch toughness shows such an increase that low alloy steel can no longer compare with it.

Universal Steels.—High alloy steels can be used with carbon as low as 0.2 to 0.15% without losing their heat-treating properties and these steels can be used equally well for case-carburizing and for heat-treated parts. It is not possible to obtain the same high strength in these steels when hardened and annealed as in the higher carbon steels, but they have the big advantage that it is not necessary to carry stocks of both high and low carbon steel with the consequent danger of getting them mixed. A number of steel manufacturers have therefore brought on the market these so-called universal steels, which usually have 0.15 to 0.20% C, 0.50 to 0.60% Mn, 0.8 to 1.0% Cr, and 4.0% Ni. Although they eliminate the danger of using the wrong kind of

TABLE XL.—INCREASE IN TOUGHNESS BY HEAT-TREATING HIGH ALLOY CHROMIUM-NICKEL STEEL

1. COMPOSITION

	Carbon, Per Cent	Manganese, Per Cent	Chromium, Per Cent	Nickel, Per Cent	Silicon, Per Cent	Phosphorus, Per Cent	Sulphur, Per Cent	Copper, Per Cent
A	0.61	0.55	0.86	1.37	0.30	0.021	0.011	0.13
B	0.48	0.59	1.04	1.62	0.33	0.019	0.010	0.06
C	0.32	0.55	0.66	3.10	0.30	0.015	0.008	0.14
D	0.26	0.65	0.86	3.62	0.22	0.018	0.008	0.10

2. AFTER HEAT-TREATING TO GIVE STRENGTH OF 120 000 LB. PER SQ. IN.

	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent	Notch Toughness, Ft.-lb. per Sq. In.		Number of Strokes, Fatigue Test
			10× Diam., Per Cent	5× Diam., Per Cent		a	b	
A	109.5	122.5	16.6	21.6	51.0	1420	1180	28 423
B	105.5	130	17.4	22.8	66.0	1605	1420	30 759
C	110	127	15.8	20.9	61.0	1410	1360	53 953
D	115.5	127	17.8	22.2	58.5	1630	1560	41 546

3. AFTER HEAT-TREATING TO GIVE STRENGTH OF 142 000 LB. PER SQ. IN.

	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent	Notch Toughness, Ft.-lb. per Sq. In.		Number of Strokes, Fatigue Test
			10× Diam., Per Cent	5× Diam., Per Cent		a	b	
A	133	142	11.6	16.0	41.7	695	514	47 676
B	124.5	137	12.0	18.0	53.5	873	710	42 067
C	131	149	13.5	18.5	60.1	1120	1020	68 700
D	136	143	12.6	18.0	57.4	1145	1050	63 853

material, it should be remembered that they are comparatively expensive and that the strength obtainable by heat treatment is low.

The Air-hardening Steels.—Air- and oil-hardening steels belong only partly to the class of heat-treating steels. Air-hardening steel was developed for those purposes where the wear, although not excessive, was still too high for heat-treated steel, and they are now made by all steel companies. They have the following analysis: 0.30 to 0.40% C, 0.50 to 0.60% Mn, 1.2 to 1.6% Cr, 4 to 4.5% Ni. These steels are very sensitive to irregularities in heating. They must be forged slowly and uniformly and the forging temperature must not go beyond the limits of 900 to 1000° C. (1650 to 1830° F.). Cold forging, which is ordinarily used to obtain exact dimensions, must be avoided on account of the danger of forming cracks. These steels offer about the hardest problem in a steel plant. Their properties are about as given in Table XLI. For most purposes they are too brittle at

TABLE XLI.—PROPERTIES OF AIR-HARDENING STEEL

	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent	Notch Toughness, Ft.-lb. per Sq. In.
			10× Diam., Per Cent	5× Diam., Per Cent		
Annealed	71-107	100-128	12-16	18-22	60-70	560-936
Air-hardened . . .	185-199	242-284	5-6	7-19	20-25	234-468

a strength of 240 000 to 285 000 lb. per sq. in. and have to be tempered in oil until they come to about 170 000 to 200 000 lb. per sq. in. It is sometimes found very difficult to anneal them if a strength of 115 000 lb. per sq. in. is desired. The proper annealing temperature is 540 to 560° C. (1005 to 1040° F.). If the steel is annealed at a higher temperature, as is done with chromium-nickel steel, it will not be possible to bring the strength down below 115 000 lb. per sq. in. For hardening, the parts are heated to 800° C. (1470° F.), and it is essential that the heating shall be slow and uniform. The parts are hardened by being removed from the furnace and cooled in air. While cooling they should be

supported so that they will not warp because of their own weight. The advantage of using these steels is that they can be hardened without warping; however, the surface can not be made file hard. The high price of this type of steel and the great difficulty in hardening and forging it are factors limiting its use.

The Oil-hardening Steels.—The oil-hardening steels, which are used to a considerable extent in America, have thus far found but little application in Germany. Steels which can be hardened by quenching directly in oil are made by various steel companies. Generally speaking, these steels are heat-treating steels, such as the chromium and the chromium-silicon steels mentioned before, which can be tempered at a low temperature and thus retain high strength. These steels are made in America with 0.40 to 0.50% C, and alloys as 2% nickel. The experiments of the authors showed that, contrary to American practice, it was desirable to keep the carbon and other components low. Thus, a steel of 0.3% C, 0.60% Mn, 0.70% Cr, 1.5% Ni had the following properties:

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Re- duc- tion, Per Cent	Notch Tough- ness, Ft.-lb. per Sq. In.
			10× Diam., Per Cent	5× Diam., Per Cent		
Annealed	44.7-71	71-100	18-22	24-30	60-70	701-936
At 850° C. (1560° F.), hardened in oil	199-227	227-242	6-7	10-12	25-40	234-375

This steel can be highly recommended, and can be used for various purposes, since it has excellent properties when heat-treated to give high strength. On account of the low alloy content of these steels they are comparatively cheap and they are not sensitive to the temperature of working. Their only disadvantage is that they warp, but this can be avoided by using jigs, since for automobile construction quantity production will make that possible. These steels are just beginning to be used for direct hardening, and it is to be expected that on account of the easy heat treatment they will come to occupy an important place in the automobile industry.

Besides the alloys mentioned, various other alloying elements have been tried and given up again because their use did not add any special quality to the steel, or because they were too expensive. Molybdenum and vanadium alone have retained their places. In America these elements were first used to any considerable extent. They are used only in small quantities, and their importance is due less to their actual presence in the finished metal than to their purifying qualities. Recently some German steel companies have commenced to make vanadium steel with 0.15 to 0.2% vanadium. The effect of the vanadium itself can not be definitely stated, since steel melts to which it is to be added are very carefully made and deoxidized. Steel of the same analysis and made with equal care without the addition of vanadium would be very likely to have equally good properties.

The Molybdenum Steels.—Molybdenum, too, is little used in Germany on account of its high price, but is largely used in

TABLE XLII.—PROPERTIES OF ENGLISH CHROMIUM-NICKEL-MOLYBDENUM STEEL

(a) 0.31% carbon, 0.67% manganese, 0.19% silicon, 0.69% chromium, 2.47% nickel, 0.60% molybdenum, 0.028% phosphorus, 0.016% sulphur, 0.06% copper

Tempering Temperature		Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
Deg. C.	Deg. F.			10×Diam., Per Cent	5×Diam., Per Cent	
450	840	181	190	6.8	11.0	49.0
500	930	169	183	6.2	11.1	50.1
550	1020	167	178	9.4	14.4	53.6
600	1110	155	168	10.2	15.2	50.6

(b) 0.44% carbon, 0.75% manganese, 0.18% silicon, 0.65% chromium, 2.42% nickel, 0.59% molybdenum, 0.027% phosphorus, 0.16% sulphur, 0.6% copper

450	840	193	215	5.7	9.0	38.3
500	930	181	195	8.4	12.4	40.8
550	1020	179	189	8.2	13.2	47.5
600	1110	162	175	8.1	13.6	52.8

America. Molybdenum is believed to reduce the annealing brittleness, that is, the low resistance of notched pieces to sudden loads after slow cooling from the annealing temperature. The results in Table XLII were obtained in investigations of chromium-molybdenum steel as used in England for high heat-treating purposes. The steel was hardened in oil at 850° C. (1560° F.) and tempered to the temperatures given in the table. These values do not show any superiority over molybdenum-free steels, and it remains to be seen what large scale tests will show.

THE HEAT TREATMENT

Heating for Hardening.—The heat treatment of steel requires great care and much experience. For successful heat treatment, the hardening operation should give a very uniform structure, with as deep and complete a transformation to martensite as possible. The heating to the hardening temperature should be as uniform as possible with an even distribution of heat around the piece. The piece while being heated should be so placed that it will not sag, with supports if necessary.

Rolled bars are heat-treated as they come from the rolling mill, so that differences in hardness will be removed by the heating for hardening. Forgings are best preheated before heating to the hardening temperature if the sections are complicated. Frequently forgings are covered with a thick coat of scale which reduces the conduction of heat away from the piece during hardening and results in soft spots. This scale should therefore be removed before hardening.

Heat Treatment before and after Machining.—It is frequently a question whether to heat-treat parts before or after machining. If the parts are heat-treated to give high strength, it will be very difficult to machine them. The upper limit to which it is possible to machine steel may be estimated to be 185 000 to 200 000 lb. per sq. in., but the economic limit is much lower, about 115 000 to 150 000 lb. per sq. in. On the other hand, it is seldom possible to heat-treat fully finished parts because their complicated form usually makes it difficult to harden them without serious warping. It is fairly easy to remedy slight warping by machining off excess material, but straightening of the finished piece is apt to be harmful to the metal. However, if the rough forgings are hardened before machining, the hardness of the finished piece is not as uni-

form as that of pieces hardened after finishing, and it is also considerably more difficult to machine the hardened pieces. High alloy steels will have to be annealed after forging before they are machined because of their high hardness. The best procedure for most steels is to anneal the parts first, then machine roughly to size, then heat-treat, and finally machine to the finish dimensions. They should be machined before hardening just enough so that the cost of the finish machining will not be too great. Parts that can be made from bars should always be cut from stock that has been heat-treated to the required strength. In the case of hot-rolled bars, there is no danger of forming soft spots in hardening because the scale falls off in rolling, except in the case of the low carbon chromium-nickel steels (0.20% C max.) from which the scale does not readily break off. These latter steels, however, are not much used for heat-treating.

Hardening Temperature.—The hardening temperature for different steels varies from 780° to 850° C. (1435° to 1560° F.) and is different even for the same kind of steel according to the section. For automobile parts, the largest section encountered is about 4 in. in diameter, and for sizes no greater than this there is but little difference between the properties of the core and of the outside. Good toughness depends upon complete hardening; therefore, the part should be hard over the whole section, with no free ferrite. It is accordingly better to harden in water and temper to a high temperature than to harden in oil or air and temper at a lower temperature. The milder the quench, the higher the hardening temperature must be; and even if the normal hardening temperature is exceeded by 30 to 50° C. (85 to 120° F.) it will do no harm. Sisco published the following figures determined on a nickel steel of 0.24% C, 0.61% Mn, 3.52% Ni (Table XLIII). The normal hardening temperature of this steel is about 820° C. (1510° F.). It is evident that only with the lowest tempering temperature was there any effect resulting from exceeding the normal hardening temperature.

The method of quenching is varied according to the final strength desired and to the type of steel being hardened. Straight carbon steels are, without exception, quenched in water, as are also the soft chromium steels. The harder chromium steels may be quenched in oil, but the quenching temperature must be high, around 850° C. (1560° F.). Chromium-nickel

TABLE XLIII.—EFFECT OF VARIOUS HARDENING TEMPERATURES ON THE PROPERTIES OF NICKEL STEEL OF 0.24% C, 0.61% MN, 3.52% NI

Hardened in Oil at		Tempered at 425° C. (790° F.)		Tempered at 535° C. (1000° F.)		Tempered at 645° C. (1190° F.)	
Deg. C.	Deg. F.	Izod Impact Test, Ft.-lb. per Sq. In.	Rockwell Hardness	Izod Impact Test, Ft.-lb. per Sq. In.	Rockwell Hardness	Izod Impact Test, Ft.-lb. per Sq. In.	Rockwell Hardness
775	1430	342	35.3	547	26.0	614	17.5
790	1455	332	35.9	529	26.7	632	18.3
815	1500	327	35.0	533	26.8	641	18.2
845	1550	316	36.6	520	27.6	641	16.7
860	1580	271	37.5	533	26.6	650	17.5
875	1610	276	36.2	524	27.3	645	17.4
885	1625	275	37.5	510	27.0	650	17.3

steels are always hardened in oil but the lower alloy steels should be quenched from a higher temperature. Parts which must be prevented from warping are always quenched in oil and should preferably be held in jigs, but if they are of a complicated shape warping can not be entirely avoided.

Drawing after Hardening.—The parts are tempered or drawn after hardening. The strength obtained is not only a function of the tempering temperature but also of the time and of the size of the part. The best procedure is to keep the temperature rather low, 550 to 580° C. (1020 to 1075° F.) and extend the time. The Brinell test makes it possible to determine when the tempering has been carried far enough to give the desired strength. This low-temperature tempering reduces the danger of making the steel too soft, especially when high strength is desired. The proper time and temperature for obtaining the required strength for any lot of material can only be found by trial. If the parts of a certain lot are all from the same melt and of the same size, the conditions, when once determined, can be used for treating all the parts of that lot, since the time and temperature that are best for one will be correct for the rest.

Annealing Brittleness.—The velocity of cooling after tempering has a large effect on the toughness. If the steel is cooled slowly it will be brittle if a notch test is made, although the tensile

strength test will give normal elongation and reduction of area, thus indicating toughness. The notched test specimen after breaking shows a granular fracture without any indication of fiber. This behavior of the steel is called annealing brittleness. If the metal is cooled rapidly, for example, by quenching in water, this brittleness will be entirely avoided.

The experimental work of R. H. Greaves¹ on this subject is especially noteworthy. His steel had the following composition: 0.26% C, 0.66% Mn, 0.07% Si, 0.84% Cr, 3.53% Ni. These

TABLE XLIVa.—RELATIONS BETWEEN COOLING AND BRITTLINESS

(By Greaves)

	Hardening Temperature (in Oil)		Tempering Temperature		Chilling	Yield Point, 1000 Lb. per Sq. In.		Strength, 1000 Lb. per Sq. In.		Elongation: American Gage Length, Per Cent		Brinell Hardness		Izod Impact Test, Ft.-lb. per Sq. In.	
	Deg. C.	Deg. F.	Deg. C.	Deg. F.		Cross	Length	Cross	Length	Cross	Length	Cross	Length	Cross	Length
1	850	1560	650	1200	Oven	85	85	108	108	22.5	25.0	237	240	60.6	935
2	850	1560	650	1200	Water	87	87	110	110	21.0	25.0	240	248	468.0	667
3	1000	1830	650	1200	Air	115	88	104	111	21.0	25.0	247	250	210.0	327
4	1000	1830	650	1200	Oven	82	85	108	108	21.0	25.0	239	240	468.0	714
5	1000	1830	650	1200	Oven	85	85	105	108	21.0	27.0	238	239	42.0	61
6	{ As No. 4, then re-heated to 650° C. }				Water	82	82	108	107	22.5	25.0	234	236	28.0	70
7					Water	81	82	105	108	20.0	28.0	233	236	468.0	634

tests demonstrate that the tempering brittleness is indicated only by the toughness, while the tensile strength remains normal. The more rapid the cooling from the tempering temperature, the greater is the toughness; and the temperature of hardening has no effect at all.

In order to find the influence of the tempering temperature, Greaves tested the same steel with the results noted in Table XLIVb. These figures show clearly that when tempering above 450 to 500° C. (840 to 930° F.) it is necessary to cool rapidly if tempering brittleness is to be avoided. Below this temperature the rate of cooling has no influence.

There is considerable lack of agreement as to the cause of tempering brittleness. It has been traced back to the melting,

¹ (1919) *Engineering*, p. 461; *Iron and Coal Trade Rev.* (1919), p. 373. P. Oberhoffer, *Das schmiedbare Eisen*, p. 473.

TABLE XLIVb.—EFFECT OF TEMPERATURE OF TEMPERING

(By Greaves)

Treatment	Brinell Hardness	Izod Impact Test, Ft.-lb. per Sq. In.
At 1000° C. (1830° F.), hardened in oil, tempered at 670° C. (1240° F.) for 2 hours, chilled in water.	247	544
Reheated to 450° C. (840° F.), slowly cooled.....	248	505
Reheated to 508° C. (945° F.), slowly cooled.....	245	262
Reheated to 554° C. (1030° F.), slowly cooled.....	232	215
Reheated to 598° C. (1110° F.), slowly cooled.....	236	239
At 1000° C. (1832° F.) hardened in oil, tempered at 670° C. (1240° F.) for 2 hours, slowly cooled....	234	93.6
Reheated to 675° C. (1245° F.), chilled in water...	228	515
Reheated to 660° C. (1220° F.), chilled in water...	223	520
Reheated to 556° C. (1030° F.), chilled in water...	228	308
Reheated to 517° C. (960° F.).....	233	117
Reheated to 500° C. (930° F.), chilled in water....	232	145

to the annealing, to the forging, and to the microscopic structure. R. H. Greaves and I. A. Jones¹ have given the effect of the various elements upon tempering brittleness. According to their work, manganese up to 0.4% does no harm, but above that amount it increases the brittleness. Phosphorus has no effect up to 0.03%, although it is an undesirable element for other reasons. Silicon, vanadium, and tungsten have no influence, but chromium and nickel increase the effect of manganese over that in plain carbon steels. A remedy against tempering brittleness is found in molybdenum, which even in quantities as small as 0.3 to 0.5% preserves the toughness even with slow cooling. For this reason it is largely used in America.

Experiments on tempering brittleness were carried out by the authors, who followed the example of Moser, separating the working volume and the working-velocity. The results have shown that it was mainly the latter factor which decreased. For the tests, steel of the following composition was used: 0.25 to 0.35% C, 0.50 to 0.60% Mn, 0.70 to 1.0% Cr, 3.5 to 4.0% Ni.

¹ British Iron & Steel Institute Convention, May, 1925.

The steel was made from a long series of meltings which were carried out according to different methods. The pieces were hardened uniformly from 800° C. (1470° F.) in oil, annealed at 600° C. (1110° F.) for one hour, then either quenched in water or slowly cooled in ashes. The results obtained are given in Table XLV.

TABLE XLV.—TEMPERING BRITTLINESS OF STEEL IN RELATION TO MELT
(By the Authors)

Melted in	Notch Toughness, Ft.-lb. per Sq. In.			Working Constant, Ft.-lb. per Cu. In.			Working Velocity, Per Cent		
	Specimen Cooled in			Specimen Cooled in			Specimen Cooled in		
	Ashes <i>a</i>	Water <i>b</i>	<i>b/a</i>	Ashes <i>a</i>	Water <i>b</i>	<i>b/a</i>	Ashes <i>a</i>	Water <i>b</i>	<i>b/a</i>
Acid electro-furnace with solid charge.....	700-1030	935-1405	1.52	950-1185	950-1185	1.03	50-80	100	1.52
Basic electro-furnace with solid charge.....	795- 935	1030-1310	1.55	950-1125	950-1185	1.06	45-90	100	1.50
Basic open-hearth furnace.....	660-1170	700-1405	1.74	830-1065	950-1185	1.11	40-80	90-100	1.62
Basic electro-furnace with liquid charge premelted in basic open-hearth furnace.	140- 700	700-1405	3.34	237-1065	710-1185	2.55	30-80	90-100	1.70

The tests also show that the basic open-hearth process will produce good results if the melting is done very carefully. But it has been found that the metal may be spoiled to such an extent by excessive decarburization in the pre-melting furnace that even the most careful working in the electric furnace will not improve it much. The tensile strength test did not show the variation in quality of the melts. The influence of the alloying elements was not shown very well because the variation in alloy content was not great. However, it could be seen that the annealing brittleness increased with the hardness, that is, the higher the carbon, chromium and manganese, and the lower the nickel. No further report of the experimental work can be given here, since it does not fit into the scope of this book, but it will be clear from the average given that the annealing brittleness reduces principally the working velocity. Even if the theory developed by Moser is not accepted, the fact remains that the work neces-

sary to break the small pieces was the same regardless of whether the cooling was fast or slow. The larger pieces, however, did show the difference that the slowly cooled pieces had less toughness and had a fracture that was granular at least in the center, whereas the rapidly cooled pieces were all fibrous. From these results, it is seen that thin pieces do not show much annealing brittleness even if slowly cooled, but the thicker parts have to be handled with more care since they tend to cool slowly. Thin parts when slowly cooled will show 80% of the toughness they have when water cooled, but heavy parts will have to be oil-quenched after tempering if great toughness is required.

Straightening parts that warp in annealing is not difficult, but such straightened parts should always be reannealed before going

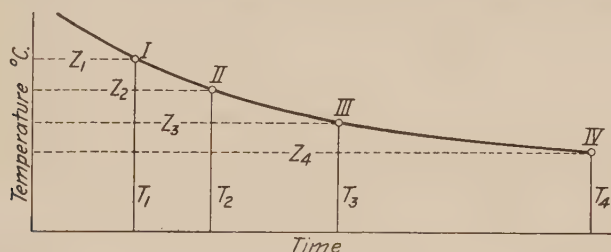


FIG. 45.—Relation of time and temperature of annealing to obtain equal strength.

to the next operation. Likewise steel that has been cooled rapidly after tempering to avoid brittleness should be heated to 450° C. (940° F.) to relieve the internal stresses. If the heating temperature stays somewhat below the tempering temperature, there will be no loss in hardness. As mentioned before, the strength obtained by tempering depends upon the temperature. Figure 45 shows the relation in the form of a chart. This relation is that for the same required strength the steel may be annealed at a temperature T_1 , for a time Z_1 , corresponding to point I, or at a temperature T_2 and time Z_2 , corresponding to point II. In figures the following temperature and time correspond:

650° C. (1200° F.)	2 hours
600° C. (1110° F.)	5 hours
550° C. (1020° F.)	10 hours
500° C. (930° F.)	20 hours

If the steel has been tempered at say 650°C. for five hours, then it will be clear that heating at 450°C. (840°F.) for one hour to remove stresses will have no effect on the strength.

The use of low alloy steels for heat-treated parts is very promising, since these steels are not expensive, are easy to produce on a large scale, and are not difficult to work and heat-treat.

5. SPRING STEELS

Importance of Good Spring Material.—Springs have to withstand changing and unexpected stresses, as do no other parts of a car, and it is hardly possible to determine the proper dimensions by calculation. Frequently in actual operation the stresses come close to the breaking stress of the material, and it is astonishing that no more care is given to the proper selection and treatment of the spring steel. It should be borne in mind that the spring is the elastic medium between the rigid car and the rough road and that it is the spring only that, by protecting the engine and driver from jolting, makes it possible to drive the automobile at a high speed. Spring tests carried out on a large scale on domestic and foreign cars have shown that good spring steel is used in high-grade cars, but that for low-priced cars the importance of the springs is sometimes not sufficiently realized.

Spring steels are, generally speaking, medium hard steels with 1 to 2% manganese, also chromium and silicon. They are rolled in strips of the required section several feet long and are usually shipped unhardened to the spring factory. The flats are cut and hot-pointed, while the main leaf is rolled to form the eyelet or else upset and punched. The holes for the bolts are punched, the leaves bent to shape and hardened at 800°C. (1470°F.), then tempered at 400 to 500°C. (750 to 930°F.). In this condition the steel has a strength of 185 000 lb. per sq. in., a yield point of 170 000 lb. per sq. in. and still has sufficient toughness to withstand sudden loads. The figures given are required, since a very high yield point gives the only security against fatigue breaks and against permanent deflection. The strength must not be too high or the steel will lose too much of its toughness. The various kinds of spring steel show but slight difference in properties about 14 000 to 18 000 lb per sq. in. from the figures previously given, since the requirements for the spring do not allow much leeway in strength or heat-treatment.

The Straight Carbon Spring Steel.—A spring steel much used in America has about 1% carbon and 0.3 to 0.4% manganese. It has the disadvantage that it is not very tough on account of the high carbon. The use of this straight carbon spring steel can not be recommended, since it is hard to heat-treat and is too brittle to insure against breakage when suddenly stressed.

The Manganese Spring Steels.—The manganese steels are excellent for springs. Two kinds are used a low alloy variety with 0.35 to 0.45% C and 1.0 to 1.3% manganese, and a high alloy steel with 0.4 to 0.5% C and 1.8 to 2.1% manganese. The latter will meet the strictest requirements and is considered the best available spring steel. The low alloy steel with 0.35 to 0.45% C, 1.0 to 1.3% Mn, and 0.25% Si has the properties given in Table XLVI. This steel is not sensitive in heat treatment and is quenched from 780 to 800° C. (1435 to 1470° F.) in water and then tempered to a strength of 165 000 to 175 000 lb. per sq. in.

TABLE XLVI.—PROPERTIES OF MANGANESE LOW-ALLOY SPRING STEEL

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Natural hard.....	57- 64	93-100	18-22	25-30	45-55
Annealed.....	43- 50	85- 93	20-24	25-30	45-50
Spring-hard, heat-treated.....	156-171	164-178	6- 8	7-10	35-45

The higher alloy steels, with 0.40 to 0.50% C, 1.8 to 2.1% Mn, and 0.25% Si, are more sensitive in heat-treatment but when correctly handled make the best springs. They have the properties given in Table XLVII. These steels are used for springs on high-grade passenger cars and quenched from 760 to 780° C. (1435 to 1470° F.) in oil, then tempered at 450° C. (840° F.).

The Manganese-silicon Spring Steels.—The scarcity of the expensive manganese during and after the war led to an attempt to find a substitute, and silicon was found to give good results. It was not possible to replace the manganese entirely by silicon but the manganese-silicon steels were quite satisfactory for mak-

TABLE XLVII.—PROPERTIES OF MANGANESE HIGH-ALLOY SPRING STEELS

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Natural hard.....	78-107	114-142	11-14	15-20	35-45
Annealed.....	50- 64	93-107	15-19	18-25	45-50
Spring hard.....	150-178	171-200	7- 9	9-11	30-35

ing springs. The analysis of spring steels now used for light cars and for trucks is: 0.30 to 0.35% C, 0.40 to 0.50% Mn, and 1.5 to 1.8% Si; and the properties are as follows:

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Natural hard.....	64- 78	93-107	12-18	18-22	30-35
Annealed.....	57- 71	85-100	15-20	20-24	30-40
Spring hard.....	142-157	164-178	4- 7	5-10	25-35

This steel has a high hardening temperature and is quenched in oil or water from 850 to 880° C. (1560 to 1615° F.).

Another spring steel having a composition of 0.65 to 0.75% C, 0.55 to 0.65% Mn, and 1.5 to 1.6% Si; corresponds to the just mentioned spring steel, but contains more carbon. Its properties are as follows:

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Natural hard.....	93-107	142-157	10-12	12-14	20-25
Annealed.....	57- 78	100-114	10-12	12-18	25-35
Spring hard.....	142-157	171-185	4- 8	5-10	20-30

For this silicon steel the same hardening temperature is necessary as for the first one. It is quite difficult to obtain sufficient toughness with the silicon spring steels.

Of the remaining manganese silicon spring steels may be mentioned one rich in manganese having the following composition: 0.50 to 0.60% C, 1.0 to 1.2% Mn, 0.7 to 0.8% Si. Its properties are:

Yield point.....	170 000–178 000 lb. per sq. in.
Strength.....	178 000–193 000 lb. per sq. in.
Elongation: Gage length 10×diam.....	5– 7%
Gage length 5×diam.....	7– 9%
Reduction.....	20–30%

This steel is hardened in oil at a temperature of 760 to 790° C. (1410 to 1450° F.).

Generally speaking the silicon spring steels can be used for less important springs only, since their silicon content makes them too brittle for highly stressed and better quality springs.

The Chromium-silicon Spring Steels.—In addition to the manganese spring steels, chromium-silicon steels are widely used for making highly stressed springs. Their analysis is about 0.35 to 0.45% C, 0.50% Mn, 0.90 to 1.1% Cr, and 0.9 to 1.1% Si. Their properties as given in Table XLVIII.

TABLE XLVIII.—PROPERTIES OF CHROMIUM-SILICON SPRING STEELS

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Natural hard.....	71– 85	114–114	10–12	12–15	20–30
Spring hard.....	171–185	178–193	7– 9	10–12	30–40

The notch toughness of the hardened steel is between 330 and 470 ft.-lb. per sq. in. (Charpy testpiece 30 mm. square), which shows clearly its excellent properties for use in springs. It is, as are all silicon steels, sensitive to the temperature of hardening and needs careful handling. For hardening it is quenched in oil

from 820 to 850° C. (1510 to 1560° F.). To improve still further the qualities of the chromium silicon steel, the manganese may be raised to 1.0% giving the following properties:

State	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
			10×Diam., Per Cent	5×Diam., Per Cent	
Natural hard.....	78-100	121-142	10-14	12-16	20-30
Spring hard.....	193-206	214-228	5- 7	10-12	30-40

The great sensitiveness to the hardening temperature is a serious disadvantage because with the slightest departure from the correct temperature cracks will result, making the part useless.

THE MANUFACTURE AND HEAT TREATMENT OF SPRINGS

The Rolling of Spring Steel.—The working of spring steels needs more care than is usually given. It is necessary that the steel should go through the last pass in the rolling mill at as low a temperature as possible without forming cracks. Spring steel should be worked with the same care as that given to tool steel, and it should be borne in mind that a mistake in the case of the spring steel will have even more serious consequences than in the case of a tool steel. Spring steels are usually used in quantity production and the faults will show at the very end of the manufacturing process, making them very costly. Tool steel, on the other hand, is largely treated in single pieces and a mistake in treatment will affect one piece only. If a spring steel is too cold when it goes through the last pass in the rolling mill, lengthwise cracks will result, and if it is too hot the structure will be too coarse, and it will be impossible to obtain a fibrous structure on drawing. This fibrous structure can be obtained in the final hardened piece only when the heat treatment has previously produced a fine structure. Each increase in the size of the grains is harmful, and, at finish drawing, will reduce the toughness very much. An increase in the grain size may come from too hot finish rolling, from too high a hardening temperature, or from too low annealing, etc.

The Manufacture of Springs.—Harm may be done not only in rolling but in making the leaves from the bars. After cutting to length, the leaves are hot-pointed in eccentric rolls and the rounding of the ends is done in a punch press. The ends of the main leaves are formed into eyelets in special machines which either roll the ends in, or upset the ends to a certain thickness and then punch the hole. This method may be useful if it does not require too high heating of the steel, and it has the advantage that the width is not reduced as in rolling. For the center holes, the springs are heated in special furnaces and the holes then punched.

Bending of the springs is done in rolling machines. In American practice the leaves remain in the rolling machine for hardening, the advantage being that no straightening is necessary afterward, but there is the disadvantage that the steel must be heated to a higher temperature. In Europe the springs are bent to shape in the bending machine, then taken out and, with the same heat, hardened. They have to be straightened after tempering.

The Heat Treatment of Springs.—Considering the number of times the springs are subjected to heat treatment and that for the manganese steel a slight heating up to 950°C . (1740°F .) will result in a coarse-grained structure and reduce the toughness considerably, it is evident that careful control is important in all operations. The springs are drawn at 650°C . (840°F .) after being hardened, and since at this temperature the steel is not yet red, it is necessary to have a good pyrometer as is the practice in all the larger spring factories in America. In an emergency and for a small number of leaves only, they may be placed near the door of a dark furnace and rubbed once in a while with a piece of wood. When the wood begins to sparkle, the correct tempering temperature is reached and the parts can be taken out. The usual time for tempering the hardened spring is half an hour.

The Testing of Springs.—An interesting investigation of the fatigue of spring steel with 1.03% C, 0.45% Mn, 0.026% P, and 0.025% S, and the relation of the fatigue to hardness and drawing temperature was made by E. P. Stenger and B. H. Stenger,¹ see Fig. 46.

The fatigue tests were made using an Olsen machine, with

¹ *Trans. Am. Soc. Steel Treating*, 1 (1921), p. 617–38; *Stahl u. Eisen*, 44 (1924), p. 1115.

bending stresses varying between 0 and 235 000 lb. per sq. in. at 550 changes per minute. The pieces had a length of $18\frac{1}{2}$ in., a width of 2 in., and a thickness of 0.285 in. They were quenched

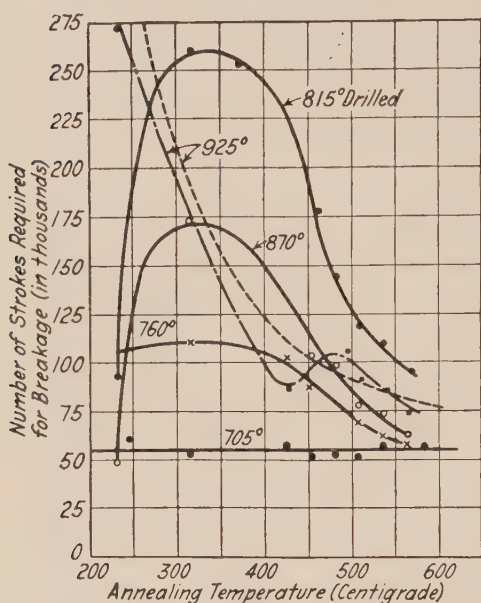


FIG. 46.—Ratio of fatigue strength and hardening temperature for a steel with 1.03 per cent carbon, 0.45 per cent manganese.

in oil from a temperature of 700 to 925° C. (1290 to 1695° F.), then tempered at temperatures from 230 to 560° C. (445 to 1040° F.). When the quenching temperature was too low (705° C.) (1300° F.) no hardening occurred and therefore tempering had no effect; and the values were all low as compared to those of hardened steel and were not influenced by the tempering. At too high a quenching temperature cracks appeared and influenced the results unfavorably. The best results were obtained by quenching

from 815° C. (1520° F.) which is in good accordance with the best hardening temperature deduced from the analysis. The authors stated that decarburizing had an unfavorable influence on the fatigue strength. This is probably due to the fact that low carbon spots do not have a high yield point when tempered at a temperature which is best suited to the remainder of the steel. The low carbon region therefore would have a low fatigue limit and cracks might start which would soon spread through the whole section, causing early failure. This condition is more apt to occur in the case of the high carbon American spring steels than in the European medium carbon alloy steels.

Further fatigue tests have been made on spring steels by R. L. Lewton,¹ using steels of the following analysis:

¹ *Trans. Am. Soc. Steel Treating*, 3 (1923), pp. 944-53; *Stahl u. Eisen*, 43 (1923), p. 1409.

	Carbon	Manga- nese	Silicon	Chro- mium
Straight carbon steel.....	0.91	0.45	0.11	.....
Chromium-manganese steel.....	0.46	0.95	0.05	0.88
Chromium-molybdenum steel....	0.48	0.95	0.24	1.22
Chromium-vanadium steel.....	0.46	0.85	0.14	1.02
Chromium-vanadium steel.....	0.49	1.00	0.26	1.18

	Molyb- denum	Vana- dium	Phos- phorus	Sulphur
Straight Carbon Steel.....			0.02	0.035
Chromium-manganese steel.....			0.02	0.025
Chromium-molybdenum steel....	0.18	.....	0.02	0.035
Chromium-vanadium steel.....		0.16	0.02	0.018
Chromium-vanadium steel.....		0.10	0.02	0.022

The tests were carried out with an Upton Lewis testing machine. The chromium-vanadium steel gave the best results.

The Grinding of Springs.—To obtain better working of the springs it is necessary to grind them on the contact surface so that they will glide easier. Grinding may be done wet or dry and across or lengthwise of the spring. If ground lengthwise, there is the disadvantage that the part near the eyes can not be ground, and if ground crosswise any marks left may be the starting point for a fatigue crack. It is now usual to clean the surface of the springs with a sand-blast so that a clean surface without grinding-scratches can be obtained. The springs are ground on both sides after being assembled; and here, too, it is necessary to take care that no marks are left to serve as the possible beginning of a fatigue break.

6. BALL-BEARING STEELS

For many years a steel with 0.9 to 1.05% carbon and 1.0 to 2.6% chromium has been used, both in America and in Europe, for making the rings and balls of ball bearings. In use this steel is hardened and but slightly tempered. Its most important qualities are hardness and durability against wear.

The Manufacture of Ball-bearing Steel.—Ball-bearing steel requires at least as much care and attention in melting and pour-

ing as does a good tool steel. First of all it is necessary to keep the melted steel hot enough for a long enough time to allow the complete solution of the added ferro-chromium. Proper melting procedure can reduce the occurrence of blowholes very much. The ingot should not be too large, because owing to the limited solubility of chromium carbide, it is difficult to homogenize the ingots by heating to a high temperature. The melting and pouring operations have such a great influence on the quality of the cast ingot that the later operations can not improve the quality but may lower it.

In forging and melting ball-bearing steel, it is necessary to watch the final temperatures as closely as in the case of tool steel. After rolling and forging, the steel is in a sorbitic or partially hardened condition due to the hardening effect of the chromium combined with the high carbon. This condition is not a good initial one for hardening, and the best results will be obtained if the structure is changed to spheroidal pearlite. This can be done by careful annealing at 720 to 730° C. (1330 to 1345° F.), the work being placed in boxes. Sometimes charcoal is added to avoid a soft skin on the parts, or the top of the boxes may be luted on with clay and gas may be passed over the parts. Temperature differences between the furnace, the box, and the various parts are unavoidable, but should be kept as low as possible. If the temperature is too high lamellar pearlite will form and free cementite will separate out at the grain boundaries, with the result that the strength can not be brought down to the required low value of 100 000 lb. per sq. in. If such a steel is hardened, this fracture will appear dull and soiled; and in order to get a better fracture the hardening temperature will have to be increased, causing much loss in toughness. If the mistake is recognized it can be easily corrected by proper heating. A correctly annealed steel should have a yield point of 57 000 lb. per sq. in., a strength of 92 000 lb. per sq. in., elongation of 18%, and a reduction of 45%. The Brinell hardness should not be below 190 or above 220, although to obtain good cutting properties Brinell hardness limits between 150 and 200 are sometimes specified.

Soft steel is generally used for the balls, and the hardness should be below 190 Brinell in the annealed state; otherwise the ends may break out in machining or cracks may occur in pressing. Above everything else, the balls should all be of the same uniform

hardness since this influences the tolerance in machining. The customer demands product uniform in hardness, hardened throughout, tough, free from slags and segregations, and uniform in hardening temperature. For use on automatic screw machines the bars must be straight. The soft skin on bars that are to be used for rings shall not be more than $\frac{1}{16}$ in. deep, and much less on bars to be used for making balls, not over 0.008 in.

Chromium Steel for Ball-bearing Rings.—For rings the following steel is used: 0.9 to 1.1% C, 0.25% Mn, 0.02% S, 0.02% P, 0.2% Si, and 1.4 to 1.8% Cr. For heavier rings the chromium content is around 1.8%.

Chromium Steel for Balls.—The steel used for making balls is of the same general analysis, but the amount of chromium varies with the diameter as given in the following list:

Diameter, In.	Chromium Content, Per Cent
0 to $\frac{3}{8}$	0
$\frac{3}{8}$ to $\frac{3}{4}$	0.6 to 1.0
$\frac{3}{4}$ to $\frac{1\frac{1}{2}}{16}$	1.0 to 1.3
Over $\frac{1\frac{1}{2}}{16}$	1.3 to 1.6

Small balls and the rings of bicycle bearings and others which are lightly stressed are made without chromium. A steel similar to common tool steel containing 1% carbon, 0.15% manganese, and 0.25% Si is used. However, this steel is of only secondary importance.

For the manufacture of rings the steel is often furnished in the form of seamless pipes.

The Hardening and Testing of the Parts.—After machining, the steel is quenched in oil from a temperature of 790 to 820° C. (1455 to 1510° F.), and then, if necessary, tempered at 150 to 200° C. (300 to 390° F.). The requirements of the hardened steel are a Brinell hardness of at least 625 and a bending stress across the fiber of at least 140 000 lb. per sq. in. This bending stress is determined by breaking hardened bars or the rings, after which the breaking stress is calculated from the load, the dimensions of the piece and the distance between the supports. The section of the piece has some influence, since it affects the depth of hardening, and the result is that the bending formula can not be readily used.

Ball Bearings from Chromium Case-hardening Steel.—In America, a chromium case-hardening steel is used for the rings of the ball bearings, and in Germany too the tapered rings used in bicycles are made from common soft steel, case-hardened. Case-hardening gives to the outer zone a composition similar to that of ball-bearing steel, but the structure will never be so fine. Nevertheless, for low stresses and where a cheap product is wanted, these rings will do.

Failures: Soft Skin and Unequal Hardness.—Serious faults in ball-bearing steel are a soft skin and varying hardness, particularly when the steel is to be used for balls. Bars with sufficient oversize to take care of the soft skin should be chosen. The steel manufacturer should of course keep the depth of the soft skin as small as possible by careful heating and rolling. Unequal hardness may come from various causes. Local decarburization may be present in the bar originally or may take place while heating for hardening. Grinding may also result in soft spots, though less frequently. Frequently segregations and poor heat treatment are responsible. Segregations may be detected by taking a disk from one end of the bar, hardening, and then breaking it. Segregations consist mainly of undissolved chromium carbide and are visible as bands in the fracture. Brilliant grains clearly shown against a dull ground in the fracture indicate an unduly high finishing temperature in rolling or forging. Unequal hardness is caused by the presence of free cementite in the steel before hardening. Free cementite may occur if rolling was finished at too high a temperature or if the annealing temperature was too high.

In the course of a very thorough investigation, H. Redenz¹ proved that parts annealed at 775° C. (1425° F.) wore more readily than those annealed at 735° C. (1355° F.). With the higher annealing temperature, the structure is no longer that of very fine and uniform granular particles of cementite; and, on hardening, large particles of cementite occur with the martensite and reduce the resistance to wear. The unavoidable temperature variations in annealing and finish rolling will be, if proper methods of checking are provided, so small that their effects will be equalized in hardening.

Unfortunately, ball bearings can not be used for crankshafts,

¹ *Stahl u. Eisen*, 44 (1924), p. 1703.

where, on account of the high speed of the shaft, they would be very desirable. Aside from the crankshaft bearings, nearly all the bearings on an automobile are ball bearings. If ball bearings were to be used for crankshafts, they would have to be very large to go over the throw of the shaft. This would make the circular velocity very high because of the large number of r.p.m. of the shaft and would result in unduly high pressure. The crankshafts may be made in parts, but this method has not been considered safe for high-speed engines. A suggestion by Stelbrecht ¹ which is very promising is to make the rings in two parts. At any rate an improvement in the crankshaft bearings would offer a chance to improve the mechanical efficiency of the engine.

7. MAGNET STEELS

Magnetism.—Steels used for their electrical and magnetic properties have a very limited application in automobile manufacture. Before the various kinds are considered, a brief explanation of the elements of magnetism will be given.

If an electric current is sent through a coil it creates an electric field the intensity of which (h) depends on the amperage (I) and the number of turns per centimeter (N) of the coil.

$$h = 0.4\pi NI$$

If a piece of iron, or other ferro-magnetic body, is inserted in a coil having a certain field intensity, then the field intensity will increase considerably. This phenomenon is called magnetic in-

duction $\mathfrak{B}$. The ratio of the induction ($\mathfrak{B}$) to the field intensity h is called the permeability (μ). It depends upon the kind of body and upon the induction. The permeability is best studied

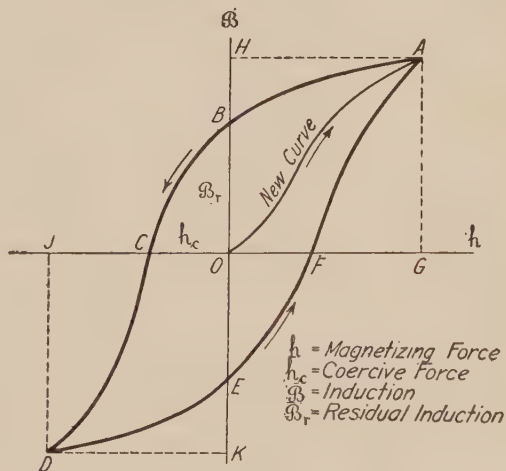


FIG. 47.—Magnetization curve.

¹ *Auto-Technik*, 1925, Nr. 12, p. 18.

by placing an iron part in a coil, through which a small increasing current is sent. The increasing current increases the field intensity from zero upward and the resulting induction is measured. The diagram in Fig. 47 shows the relationship.

If the field intensity changes from O to G (Fig. 47), the induction changes from O to H according to the line OA . This curve OA shows that the permeability is not constant. If from point A (field intensity G and induction B) the current is decreased, the induction decreases but not to the same extent. The steel retains some magnetism even if the electric field has disappeared, and this residual magnetism is expressed by the distance OB . If the direction of the current is reversed and a field of the reverse direction is created, then the induction will decrease and at the field intensity OC become zero. The distance OC is called the coercive force. Further increase in the field intensity in the same direction up to the value J brings the induction to the value K . If the field intensity decreases to zero and then increases in the opposite direction, the induction changes according to the line $DEFA$. The complete magnetic curve consists of the curve OA and the so-called hysteresis loop, which is the remainder of the curve shown in the figure. The hysteresis loop is caused by the induction lagging behind the field intensity. This hysteresis loop appears in the case of alternating current magnets (coil of the transformer) as a loss in electric energy. Different steels have to be used according to the purpose of the coil.

D.C. Magnets.—For direct-current magnets the magnetic force of the field should be increased considerably by the iron core. In this case a material should be selected which has high permeability since such a material offers the least resistance to the magnetic current. Soft pure iron is about the best material for this purpose, as alloys and impurities generally reduce the permeability. There are, however, certain alloys which at certain definite compositions have greater permeability than pure iron. Frequently cast steel is used and usually steel with low strength will be sufficient since the section will have to be much larger to meet the electrical requirements than the strength necessary would require.

A.C. Magnets, Hysteresis.—For alternating-current magnets (for example, transformer coils) the work required for remagnetizing, which may be calculated from the hysteresis loop, should

be kept as low as possible. There are certain undesirable eddy currents in the iron, caused by the frequent change in direction of the current. These eddy currents result in loss of energy. This loss of energy is shown by the fact that if a certain amount of energy is put into the primary coil of a transformer, the energy delivered by the secondary coil is less. This loss is mostly due to the work necessary to remagnetize the coil, that is, the hysteresis loss, and the loss due to the eddy currents. To reduce the hysteresis loss it is necessary to choose a steel with a small hysteresis loop. The eddy current loss may be reduced by using a steel with a high electrical resistance. By making the magnets from strips of sheet metal of the proper composition, insulated from one

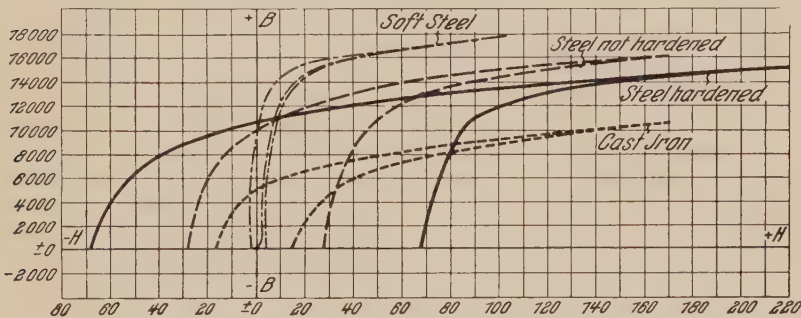


FIG. 48.—Hysteresis graphs of various steels. (From Goltze.)

another, this resistance can be made very high. The thickness of the strip should not be less than No. 00 gage. For this purpose max. 0.06% C, max. 0.10% Mn, max. 0.015% P, max. 0.01% S, and 4.0 to 4.2% Si is a good alloy.

Figure 48 shows the hysteresis loop of various steels. The watt losses in a transformer for a silicon sheet steel of No. 00 gage will be about 1.3 watt per kg. for an induction of 10 000 Gauss and 50 cycles. Suitable alloys and skilled heat treatment may bring the losses down to 1.0 watt per kg.

PERMANENT MAGNETS

Permanent magnets are of greatest importance in automobile use. They should have a high residual magnetism or remanence and a high resistance against demagnetizing, which is best

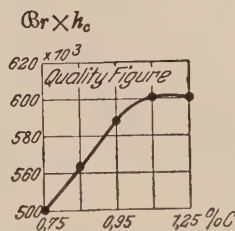
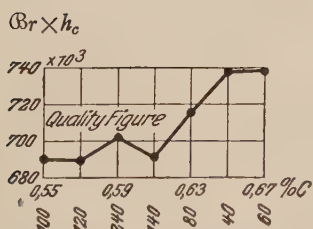
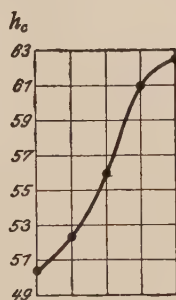
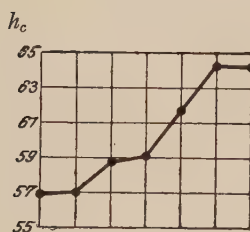
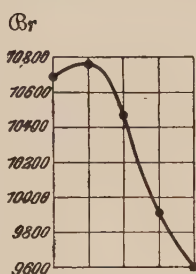
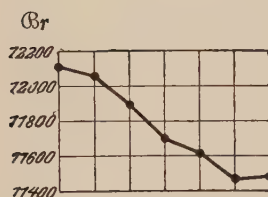
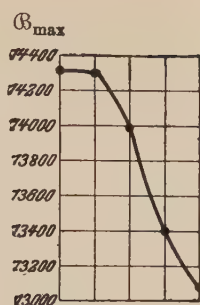
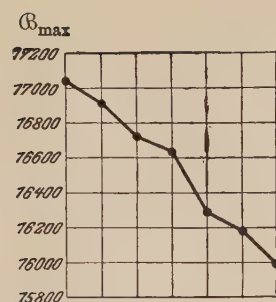
expressed as a high coercive force. The product of residual magnetism times coercive force is used as a figure for indicating quality.

Tungsten Magnets.—Until recently, chromium and tungsten steels were commonly used for permanent magnets. The first tungsten steel magnets were made forty years ago of the same composition as is used today. G. Hannack¹ published the result of an investigation of tungsten and chromium magnet steels. He gave as the temperature range for forging and rolling tungsten steel (0.55 to 0.75% C, 0.30% Mn, 0.20% Si, 5 to 6% W) the following: 750 to 950° C. (1380 to 1740° F.). It is advisable to press the parts into the final form at 800° C. (1470° F.). For hardening, the steel is quenched in water from 800 to 900° C. (1470 to 1650° F.). It does no particular harm to hold the steel at the quenching temperature for a long time, which is quite contrary to the case of chromium magnet steels. The magnetic value of the tungsten steel depend largely on the carbon content and are represented in Fig. 49.

With increasing carbon the maximum induction ($B_{\max.}$) and the residual magnetism decrease, whereas the coercive force increases. However, the product of these last two terms, which is the quality figure, increases. It is thus possible to produce steel with high residual magnetism or high coercive force by changing the carbon content. If the carbon is made as high as 7% the quality figure reaches the high value of 750 000, but the rejections in hardening are so high that this steel is not economical.

Chromium Magnets.—Chromium magnet steels were developed as a substitute for the tungsten type. They have 1% carbon and 1.0 to 2.0% or sometimes up to 5% chromium. Figure 49 shows the effect of the carbon content, which is about the same as in the case of the tungsten steels except that the maximum values are lower. The best composition of chromium steels for magnets is 1.0 to 1.1 carbon and 1.8 to 2.2% chromium. The temperature for rolling these steels is about 900° C. (1650° F.), and it is hardened in oil from 800 to 820° C. (1470 to 1510° F.). They are very sensitive to the hardening temperature and too long heating at high temperature, which is not the case with the tungsten magnet steels. Increasing the chromium increases the magnetic properties considerably but the same difficulty in hardening occurs as in the tungsten steels when the carbon is increased.

¹ *Stahl u. Eisen*, 44 (1924), p. 1237.



Number of values used to obtain the average.
Tungsten steel magnets

Number of values used to obtain the average.
Chromium steel magnets

FIG. 49.—Magnet steels.

A comparison of the two steels shows that their magnetic properties are alike but that chromium steel is much more sensitive in hardening. Except for very simple forms which are easy to harden, tungsten steel is superior on account of the high hardening loss in the chromium steel and the decreasing price of the tungsten steels. For very complicated forms which would be difficult to forge or press, cast magnets may be used satisfactorily.

Cobalt Magnets.—The cobalt magnet steels, which were discovered only a few years ago, have thoroughly revolutionized the field of magnet steels. Their excellent properties are shown in Table ¹ XLIX.

TABLE XLIX.—ELECTRIC PROPERTIES OF MAGNET STEELS

	Residual Magnet- ism	Coercive Force	$B_r \times h_c$ $\times 1000$
Carbon steel, with 1.2% carbon.....	8 110	60	487
Chromium steel, with 2.0% chromium.....	11 225	61	732
Tungsten steel, with 5.0% tungsten.....	11 100	65	722
Cobalt-chromium steel, with 18.0% cobalt..	10 650	145	1544
Cobalt-chromium steel, with 35.0% cobalt..	9 130	203	1853

The best known of these steels are those first made by the Japanese with 0.5 to 0.8% C, 1.5 to 3.0% Cr, 3 to 5% W, and 20 to 60% Co. The scientific knowledge concerning these steels was greatly increased by the research work of Gumlich who showed that the best properties could be obtained by magnetizing to a much higher value than for the usual magnet steels (200 to 1100 Gauss). He also showed that the cobalt could be partly replaced by the less expensive chromium, resulting in considerable saving in cost.

As shown in the table the remanence of the cobalt steel is lower but the coercive force much higher than for the common magnet steels. However, the cobalt steel is greatly superior since the figures given refer to the true remanence, which is always greater than the apparent remanence. The apparent remanence depends upon the form of the magnet and its magnetic curve, and approaches nearer to the true remanence as the ratio

¹ F. Rapatz, Die Edelstähle, p. 16.

of length to diameter of the magnet increases and the coercive force of the material becomes greater. Thus it will be seen that although the true remanence of cobalt steel is smaller than that of chromium steel, the remanence of cobalt steel magnets of 18 cm. length (7 in.) and 0.6 cm. diameter ($\frac{1}{4}$ in.) is 9% greater and for 6 cm. length and 0.7 cm. diameter is 13% greater than for chromium steel magnets. Cobalt steels have the great advantage of being nearly immune to vibrations, and this combined with their greater suitability for short magnets makes them superior to the magnet steels previously used. It is now possible to make the magnetic field from permanent magnets and to have them rotate, while the parts carrying current are allowed to remain stationary. This method of construction results in greater simplicity of design. The use of cobalt steel will expand in spite of its high cost, particularly where small size is desirable.

8. VALVE STEELS

The Working Conditions of Valves.—Although for machinery steel in general only the properties at room temperature are of interest, in the case of valve steels it is necessary to consider the properties at higher temperatures. The cooling system carries the heat of combustion of the fuel away from the cylinder walls, and the piston is favored by its mass, but for the valves neither of these factors is present. The intake-valves will not be excessively heated since they are cooled by the cool gas at each intake. The exhaust valves, on the other hand, are exposed to the heat of combustion and are surrounded by hot gas when they open. These valves are a difficult problem both for the designer and the steel maker. The only possible cooling is through contact with the seat and by conduction along the stem down to the guides. The higher the speed the faster the explosions follow each other and the less chance there is for cooling, consequently the more the valves are heated. To improve the efficiency of the engine it is necessary to work at higher temperatures, and this calls for suitable material. The temperature of the valves in an automobile engine depends upon the way the car is operated. If it is driven on level road at a high rate of speed the valves will become dark red after long driving, but when a heavily loaded car climbs up a steep grade the temperature may rise under unfavorable conditions to a cherry red.

The Requirements for Valves.—To enable an engine to perform properly at high temperature the valves must fulfill the following requirements:

1. High thermal conductivity.
2. Resistance against the impact stress caused by the valve hitting continuously against the seat at high temperature.
3. Resistance against corrosion by the hot exhaust gases.
4. Sufficient hardness to give a smooth frictionless guide.
5. Small specific weight.

Actual valve requirements are generally limited to good strength at high temperature. The steels are tested by placing the speci-

TABLE L.—TENSILE STRENGTH OF VALVE STEEL FOR VARIOUS TEMPERATURES

Carbon	Chromium	Nickel	Vanadium	Strength in 1000 Lb. per Sq. In. at*					
				20 68	200 390	300 570	500 930	600 1110	700° C. 1290° F.
0.20	.....	.....	.....	66.7	76	68.5	35.2	6.7	.....
0.31	1.53	1.9	.....	123	122	121	64.1	35	13.4
0.21	1.69	4.0	.....	111	102	104	61.2	28.8	11.4
0.37	2.38	.....	0.58	182	175	171	107	58.2	10.7
0.12	15.8	1.5	.....	112	.....	95	73.6	29.7	11.5
0.28	20.6	5.76	.....	123	.....	90.7	85.6	67	34.3

Carbon	Chromium	Tungsten	Nickel	Strength in 1000 Lb. per Sq. In. at†				
				700 1290	800 1470	850 1560	900 1650	950° C. 1740° F.
0.6	.....	4.0	.....	38.4	22.8	25.0	20.0	16.0
0.35	13.0	.....	.....	27.1	15	.....	11.1	9.25
0.6	7-12	.....	.....	33.5	18.5	21.4	17.1	14.2
0.35	.....	.....	3.0	25.7	.....	.....	10	.....
0.15	1.0	.....	3.75	22.8	15.7	11.4	10	7.12

* F. Rapatz, *Die Edelstähle*, p. 7; Edert, *Stahl u. Eisen*, 42 (1922), p. 962.

† E. Gabriel, *Iron Age*, 1920, Dec. 2, pp. 1465-69; *Stahl u. Eisen*, 41 (1921), p. 1861.

mens in a tensile testing machine and heating them with an electric furnace. The hot strength can not be exactly determined by the tensile strength test, because the time is an important factor. If the stress is increased slowly a point is reached at which the piece becomes longer without any additional load. This stress is called the viscosity limit or true hot strength. Its determination is complicated and requires much time even when the latest procedure as given by Pomp is followed. The values found by the common breaking test are much higher than the viscosity limit, and have the great disadvantage that they can be readily compared only when determined under identical conditions.

If the material does not have sufficient strength when hot, the head will get out of shape and the valve stems become longer, requiring continuous adjustment to keep them tight. When the valve hits against the seat the stem is almost unavoidably eccentrically stressed, so that steel with a high elastic limit and yield point is the only security against breakage.

Chromium-nickel Steel for Valves.—The material formerly used for valves was chromium-nickel steel, a typical composition being: 0.15% C, 0.50% Mn, 1% Cr, and 4% Ni. This steel is still being used for intake valves but is not satisfactory for exhaust valves in the present higher-speed engines. High-speed steel was tried because of its well-known property of retaining its strength at high temperature. Also tests were made using the non-magnetic 25% nickel steel which was known to have little tendency to scale.

Chromium Steel for Valves.—However, only a high chromium steel with 1.5% carbon and 13% chromium gave satisfactory results. The softer chromium steels of compositions similar to the ordinary stainless irons and steels were not very successful. Table LI gives data obtained by E. Gabriel showing the relative suitability of various steels for this purpose. No. 1 indicates the best and No. 5 the least suitable property.

The high carbon-chromium steel formerly used for valves had the following composition: 1 to 1.5% C, 0.50% Mn, 0.50% Si, 10 to 15% Cr, and 0.2 to 0.5% V or 3% Co. This steel is very sensitive to forging and must not be heated above 900° C. (1650° F.) or it will crumble under the hammer. The annealing range is 750 to 800° C. (1380 to 1470° F.) and the lowest obtainable strength about 114 000 lb. per sq. in. The finished valves

TABLE LI.—RELATIVE SUITABILITY OF SOME STEELS FOR VALVE USE

Properties	Composition, Per Cent					
	0.6	0.35	0.6	0.35	0.14-0.13	Carbon
	3.5	13.0	7-12	.....	1-1.4	Chromium
	.....	.....	.....	3.0	4.0	Nickel
	14-17	.....	.....	.....	.....	Tungsten
High strength at high temperature.....	1	3	2	4	4	
Forgeability.....	4	3	4	1	2	
Ease of heat treatment.....	2	1	2	4	3	
Oxidizing.....	3	1	2	4	4	
Resistance to lengthening....	1	1	1	2	2	
Wear in the guide.....	1	3	1	2	2	
Machinability.....	3	1	5	2	4	

are quenched in oil from 900° C. (1650° F.), and annealed at 550 to 600° C. (1020 to 1110° F.). It should be remembered that because of the high temperature of the valves when in use the annealing effect continues and that if heated above the transformation point a chilling effect will take place when the engine is shut off. Therefore definite specifications of strength and hardness apply only to the stem, and for the rest of the valve the heat treatment only serves to give a uniform structure.

Stainless Steel for Valves.—Stainless steels were tried for valves because of their resistance to heat and oxidation. Tests with alloys of 0.15% C, 13% Cr, and 10 to 20% Mi or 0.35% C, 20% Cr, and 5% Ni were partly successful, but there was the disadvantage that the stem surfaces were too soft and had a tendency to stick in the guide.

Tests with High Alloyed Chromium-nickel Steel with Tungsten.—An improvement was effected by the addition of tungsten, giving a steel of the following analysis: 0.40 to 0.50% C, 0.50 to 1.0% Mn, 12 to 15% Cr, 12 to 15% Ni, and 2.5 to 3.5% W. This proved to be quite successful, the tungsten increasing the hardness so that the stem did not stick in the guide, while the resistance to scaling was retained.

A comparison of all valve steels thus far mentioned is given in Table LII.

TABLE LII.—PROPERTIES OF VALVE STEELS OF VARIOUS ALLOYS AT VARIOUS TEMPERATURES

Car- bon, Per Cent	Man- ga- nese, Per Cent	Sili- con, Per Cent	Chro- mium, Per Cent	Nickel, Per Cent	Tung- sten, Per Cent	Vana- dium, Per Cent	Phos- phor- us, Per Cent	Sul- phur, Per Cent	Micro- structure	Strength at Temperatures				Run- ning Time, Hours
										600°C. 1110°F.	700°C. 1290°F.	800°C. 1470°F.	900°C. 1650°F.	
										1000 Lb. per Sq. In.				
0.30	0.80	0.15		25.30			0.020	0.006	Austenite	43	35.5	24	11.4	20-25
0.56	0.28	0.25	4.59		18.32	0.15	0.025	0.008	Double carbide in sorbite ground	68	38.5	20	15.7	20-30
0.45	0.50	0.73	13.35	0.27			0.022	0.015	Granular pearlite.	65	37	21.5	20	20-35
0.56	0.31	0.28	12.98			0.18	0.027	0.011	Granular pearlite.	67	34	21.5	21.4	30-40
1.36	0.35	0.29	8.97	0.16			0.032	0.017	Double carbide in sorbite ground	71	43	18.5	17	40-70
1.85	0.47	0.15	9.25			0.09	0.021	0.008	Double carbide in sorbite ground	85	33	21.5	18.5	50-70
1.63	0.54	0.63	12.37	0.11			0.037	0.018	Double carbide in sorbite ground	74	43	24	21.4	50-70
0.13	0.53	0.47	12.76	1.68			0.023	0.031	Ferrite and granu- lar cementite	93	43	24	22.8	60-100
0.34	0.56	0.39	17.38	5.74			0.029	0.016	Austenite	85	57	43	28.5	80-120
0.41	0.49	0.54	12.36	14.81			0.024	0.011	Austenite	100	71	50	35.5	100-150

Tests with Various Materials.—M. Mahoux¹ has made a series of tests using valves made from various materials. The results are given in Table LIII. The tests were run for a period

TABLE LIII.—TESTS ON VALVES OF VARIOUS MATERIALS

Material	A	B	C	D	E	F	S	U	Sil-chrome
Carbon.....	0.39	0.48	0.51	0.72	0.7	0.51	0.42	0.08	0.44
Chromium...	0.35	3.46	10.14	4.96	5.0	2.08	2.47	11.60	9.04
Manganese...	0.19								
Silicon.....	0.18	0.41	0.24	0.58	0.34	0.68	0.12	0.13	2.67
Nickel.....	4.12		45.0	traces				22.64	
Tungsten....	2.54	15.61		17.15	17.0	13.0	15.87	10.97	
Vanadium....				0.88	0.5	0.78			traces
Molybdenum.									0.17
Phosphorus..	0.019	0.028	0.017	0.009		0.018	traces	0.013	0.012
Sulphur.....	0.02	0.02	0.034	0.018		0.052	0.02	0.038	traces
Order in quality.....				2	4	3	5		1

The following notes apply to the table:

A. Assembled, air-hardened. Annealed at 560° C. (1020° F.) with notch toughness 375 ft.-lb. per sq. in., 185 000 to 200 000 lb. per sq. in. strength. Head deformed, stem froze.

B. Assembled annealed. Head deformed. Stem froze.

C. Assembled with forging hardness with 115 000 lb. per sq. in. Valve froze and did not close any more.

D. Heat-treated to 140 000 lb. per sq. in. Head stood up. Stem excellent. Seat O.K. Notch toughness of the steel only fair.

U. Valve froze. Material showed deep pits due to corrosion. No deformation of head. Corrosion worse than for preceding material.

E. Somewhat worse than D. Did not freeze but material did not smooth as well. Deformation of head was small.

S. Grooves from freezing deeper and greater tendency to oxidize than E.

Silchrome. Excellent valve. Good closing at high temperature. Cooling during suction and compression stroke good in spite of small thermal conductivity as compared with high-speed steel. Valve remained black.

of fifty hours, and then the valves were inspected, special attention being given to the head, the stem, and the guide. The guide was made of a soft cast iron for valves A, B, and C, and of a high

¹ *Revue de Metallurgie*, 22, année, Januar, 1925, p. 39-51.

quality phosphorus bronze for the rest. Of the valves *A* to *U*, valve *D* stood up best and *F*, *E* and *S* were next best. The "silchrome" valve gave the best results. The composition of the metal is given in the last column of the table. Its transformation temperature is about 935° C. (1715° F.).

Requirements of valve steel are high elastic limit for the stem, and sufficient hardness at high temperature and good heat resistance for the part exposed to the flame. A minimum notch toughness of 185 to 280 ft.-lb. per sq. in. and resistance to scaling and to chemical attack by the gases are other requirements.

The specific gravity of the chromium-silicon valve material is 7.62 while that of steel *D* is 8.69. The weight of the chromium-silicon valve is therefore less by 413 gr.

Chromium-silicon Steel.—At the present time a high chromium steel with 1.5% carbon is most commonly used for valves. This steel is inferior to high chrome-nickel steel, but cheaper; further, there is in use a chromium-silicon and chromium-nickel steel containing some tungsten. Unfortunately there have been no comparative tests of these steels published up to the present time, but the general opinion seems to be that the chromium-silicon steel is very good.

Interesting tests on valve steels by J. B. Johnson and S. A. Christiansen¹ are reported briefly in Table LIV. The tests show that the chromium-nickel steel has the highest tensile strength. Pitting was the same for both chromium and chromium-nickel steels. The relative suitability of the different steels was: Tungsten steels are out of the question, because they scale too much; chromium nickel steel has the disadvantage that being an austenitic steel, it can not be hardened and thus the working parts are subject to too much wear. Stainless chromium steel is hardenable and does not scale, but becomes soft at the temperature at which the engine operates; cobalt-chromium steel remains comparatively hard at high temperature but its heavy scaling after short use makes it unsuitable for valves; chromium-silicon steel softens at the engine temperature like the straight chromium steel; monel metal resists corrosion but is too soft. Thus none of the metals tested was really satisfactory.

Table LV gives the results of an investigation by the authors on valve steels. For intake valves, the common low alloy chro-

¹ *Stahl u. Eisen*, 44 (1924), p. 1757.

TABLE LIV.—EXPERIMENTS WITH VARIOUS VALVE STEELS

ANALYSIS OF MATERIALS

(Tests by J. B. Johnson and S. A. Christiansen)

Designation	Carbon	Manganese	Silicon	Chromium	Nickel	Others
Tungsten steel	0.50- 0.70	0.30	.....	3.0- 4.0	.....	Tungsten 15- 18
Chromium steel	0.25- 0.40	0.50	.....	11.5- 14.0	.....	.....
Silicon-chromium steel . .	0.45- 0.60	0.50	2.75- 3.75	7.0- 9.0	.....	.....
Chromium-nickel steel . .	0.30- 0.40	0.50	3.00- 4.00	15.0- 20.0	24-26	.....
Cobalt-chromium steel . .	1.00- 1.50	0.50	0.40- 0.60	10.0- 13.0	.....	Molybdenum 0.60-0.90; Cobalt 3.0- 3.50
Monel metal . . . . .	.....	3.50	0.50	.....	60.0	Copper 23.0; Iron 3.5

STRENGTH OF MATERIALS AT HIGH TEMPERATURES

Designation	Temperature		Strength, 1000 Lb. per Sq. In.
	Deg. C.	Deg. F.	
Tungsten steel	20	68	202
	870	1600	17.2
Chromium steel	20	68	101
	870	1600	14.7
Silicon-chromium steel	20	68	207
	870	1600	4
Chromium-nickel steel	20	68	239
	870	1600	122
Cobalt-chromium steel	20	68	18.1
	870	1600	124
Monel metal	20	68	102
	815	1480	15.8

mium-nickel steels are good enough, but if this steel is used it will be necessary to have the intake and exhaust valves of different sizes to avoid mistakes. For most cars, in which the valves are not too highly stressed, the high alloy chrome and chromium-

TABLE LV.—RESULTS OF GENERAL INVESTIGATION OF VALVE STEELS
(By the Authors)

Valve from	Analysis										Properties				Note		
	Carbon	Manganese	Silicon	Chromium	Nickel	Tungsten	Vanadium	Molybdenum	Cobalt	Phosphorus	Sulphur	Copper	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.		Elongation, Per Cent	Reduction, Per Cent
Great Britain	0.47	0.72	1.67	12.88	12.44	2.40	0.19						100	133	9.6	9.00	Said to stand high temperatures and oxidizing flames
Great Britain	0.39	0.71	1.85	12.80	12.55	2.56	Trace		Trace	0.015 0.009	0.018 0.009	0.02 0.03					
Great Britain	0.38	0.73	1.83	12.80	12.45	2.47				0.025 0.009		0.03	81	126	(10 X) 26.1	45.3	
United States	1.73	0.26	0.81	13.28				0.6	3.10	0.02							
United States	0.46	0.32	3.60	8.40													Has good reputation
United States	0.37	0.53	1.96	13.23						0.018 0.012							
Italy	0.41	0.48	0.56	0.63	4.84	2.35				0.02	0.008	0.10					
Germany	0.55	1.55	0.46	16.85	16.32	3.60							83	120	22	16	
Germany	1.03	0.44	0.33	11.03						0.013 0.007	0.028 0.019	0.09 0.18				32	
Germany	1.5	0.39	0.31	0.42	0.30					0.03 0.019	0.052			82			
France	0.6–	0.2–	0.4–	3–5		15–18	0.8–			0.006–	0.01			121–135	10*	Annealed	
	0.8	0.3	0.6				1.0			0.01				178–192	10*	925° C. air hardened, 525–560° C. drawn	

* French gage length

silicon steels are used both in Germany and America. The expensive chromium-nickel tungsten alloy valves are used only for engines with high compression which are run at high speed as in racing cars.

Besides the quality of a valve steel its heat treatment is very important and careful attention is needed during forging. The valve should be made so that the fibers do not roll in near the plate of the valve, which would give smaller strength in the seat just where the material should be best.

Attempts to make valves in two parts with the head screwed or riveted on have not been very successful. Recently the problem of making valves in two parts is said to have been solved by electric butt-welding. The head is made larger where it is to be welded and then is machined to size after welding.

The problem of the most suitable valve material does not seem to be solved as yet. This is partly due to the fact that motor design is still changing, both in America and in Europe, and the demands made on the valves are constantly increasing.

9. STAINLESS STEELS

Explanation of Rusting.—The protection of steel from rusting is important industrially and economically. Large quantities of steel are lost yearly by rusting, requiring replacement of material and making more labor necessary. Rust consists of iron oxide, and the problem of its formation has been studied for a long time but no completely satisfactory explanation of the process has been found. Certain points that have been established are that a higher temperature speeds up the process, and that it is of an electrochemical nature. In addition, certain atmospheric conditions have been found to have a great influence. Air in industrial centers makes rusting more apt to occur than does country air. In the combustion of coal there is formed some sulphur dioxide (SO_2) which is partly transformed in moist air to sulphuric acid (H_2SO_4), this acid attacking iron and steel very readily. The attack is influenced by differences in structure and composition of the iron and these differences can not be entirely avoided. The sections of different chemical composition have different electrochemical properties and this difference results in more ready rust formation.

Krupp was the first to use rust-resistant steel, and even before

the war knew the effect of a high chromium content in increasing the rust resistance. Formerly a nickel steel with 0.35 to 0.45% C, 1.5 to 2% Mn, and 25% Ni was used, but only to a minor extent because of its high cost. Also, it was not nearly as resistant to corrosion as the modern rust-proof steels.

Analysis; the Manufacturing of Stainless Steels.—The common stainless steels now used contain 12 to 15% chromium, 0.15 to 0.7% carbon. The manganese content is about 0.3 to 0.5%, and silicon about 0.25 to 0.80%, with small quantities of vanadium and nickel. By varying the carbon content, it is possible to produce stainless steel which is either very soft or which can be hardened. The carbon should not exceed 0.5%, however, because it decreases the forgeability and also the resistance to corrosion. The thermal conductivity of these steels is small; therefore they have to be heated slowly and uniformly. It is best to heat first in a furnace at 600 to 700° C. (1100 to 1300° F.) until the temperature is uniform and then to heat to the desired temperature. The best forging temperature is 900 to 1050° C. (1650 to 1920° F.), never below 850° C. (1560° F.). It will be necessary to interrupt the forging frequently and to reheat the piece to the proper temperature. On account of their air-hardening properties these steels should be cooled in the furnace or in ashes, etc.; otherwise they are apt to crack. They are annealed at about 750° C. (1380° F.). After annealing the low carbon stainless steel has a strength of 78 000 lb. per sq. in. and the harder steel with 0.5% carbon a strength of 100 000 to 114 000 lb. per sq. in.; thus machining will not be difficult.

Hardening of Parts from Stainless Steel.—After machining, these steels must be hardened if great rust resistance is desired. They should be heated with great care to 900 to 1000° C. (1650 to 1830° F.) and quenched in air, oil or brine. Small parts that crack easily are hardened in air, but the surface hardness will not be as great as when the steel is quenched in oil.

Even if the steel is quenched in oil from 1000° C. (1830° F.), it may be soft due to retention of austenite. The strength after hardening lies between 155 000 lb. per sq. in. for the soft and 240 000 lb. per sq. in. for the hard steel. The desired toughness can be obtained by suitable tempering. Owing to the greater oxidation resistance of the steel, the temper colors, which depend on the thickness of the oxide skin, appear at much higher temper-

ture than they do in the case of common steels. O. K. Parmiter ¹ gives the following figures:

	Carbon Steels		Stainless Steels	
	Deg. C.	Deg. F.	Deg. C.	Deg. F.
Very pale yellow.....	220	430	250	480
Deep straw yellow.....	230	445	300	570
Brownish yellow.....	240	465	350	660
Brownish purple.....	260	500	400	750
Red purple.....	270	520	450	840
Full purple.....	290	555	500	930
Dark purple.....	300	570	550	1020
Full blue.....	310	590	600	1110
Greenish blue.....	320	610	650	1202
Gray.....	340	645	700	1290
Brownish gray.....	360	680	750	1380

Grinding and Polishing of Parts from Stainless Steel.—Hardening does not give full rust resistance, and the steel must afterward be carefully ground and polished. The polishing must remove every particle of slag and every bit of oxide from the surface. In polishing it is necessary to consider the small thermal conductivity of the steel and to avoid overheating, which may cause annealing in spots or result in cracks. Cold-working, such as drawing and pressing, and also annealing reduce the rust resistance very much. Therefore cold-worked parts should be hardened and polished. If hardening is not possible a very soft stainless steel with 0.1% carbon, or less, and more chromium (18%) is used. This low carbon steel does not require hardening to develop its stainless properties. The lowest possible carbon content which will give the desired physical properties should be used since the corrosion resistance decreases as the carbon content increases. This is due to the fact that chromium carbide does not dissolve readily at high temperature, and complete solution of this carbide before quenching is necessary if the greatest resistance to corrosion is to be obtained. Nothing can be gained by carburizing stainless steel. The surface will become hard, but the corrosion resistance will be lost.

¹ *Trans. Am. Soc. Steel Treating*, 6 (1924), p. 315; *Stahl u. Eisen*, 45 (1925), p. 803.

Influence of Alloying Elements.—The effect of various elements on corrosion resistance may be considered. The effect of carbon in decreasing the resistance has been mentioned. Manganese has no effect and is only added to make the steel free from hot shortness. Silicon increases the resistance but can not be used to replace the chromium. It increases the ductility, requires a higher hardening temperature, and is added to soft stainless steels in which a high toughness is wanted. Phosphorus and sulphur should be present in traces only. They are harmful, particularly because they cause segregation which starts local corrosion.

Up to the present there has been nothing in the literature emphasizing the need of careful melting. The softer steels, especially, will not stand over-oxidizing. If over-oxidizing occurs it will probably not show up in the analysis but will cause cracks during heat treatment and also make the rust resistance low. The failure of stainless steel which is sometimes so mysterious can very likely be traced to a high oxygen content. Investigations along this line are very difficult and results would be hard to obtain.¹

Strength of Stainless Steel.—The strength of stainless steel is very favorable. Hultgren² gives, for a steel with the following analysis: 0.22% C, 0.07% Si, 0.13% Mn, 1.75% Ni, and 10.05% Cr, the data of Table LVI.

TABLE LVI.—PROPERTIES OF STAINLESS STEEL

(By Hultgren)

Heat Treatment	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation, Per Cent	Reduction, Per Cent	Notch Toughness, Ft.-lb. per Sq. In.
At 900° C. (1650° F.) hardened in oil, tempered to 550° C. (1020° F.), cooled in oil. . . .	120	135	16.6	58	1000
At 900° C. (1650° F.) hardened, drawn to 700° C. (1290° F.), cooled in oil.	74	105	24.3	66	1120

¹ Recent additional note of the authors: No experimental tests are available, but practical experience has proven that the properties of stainless steel are largely dependent upon the degree of deoxidation.

² Am. Soc. F. Test. Mat. 27. Convention, 1924.

High Alloy Chromium-nickel Steels.—In the chemical industry where resistance to acids is required, an austenitic chromium-nickel steel is used. It has the disadvantage that the strength is low, and its high cost will probably prevent its use in automobile manufacture. The resistance to acids is of little importance in connection with automobiles. But resistance to air and salt water are important. Table LVII gives some data on these properties.

TABLE LVII.—RESISTANCE TO AIR AND TO SALT WATER

	Relative Loss of Weight	
	In Air	In Salt Water
Soft steel.....	100	100
Nickel steel, 25% nickel.....	11	55
Steel: 0.15% C, 14% Cr, 1% Ni.....	0.4	5.2
Steel: 0.25% C, 20% Cr, 7% Ni.....	0	0.6

The excellent quality of the last steel in the table is due to its high nickel and chromium contents. But, as mentioned before, this steel will not be found suitable for automobiles and even the common straight chromium stainless steels are still considered too expensive.

Generally speaking, the application of stainless steels is most promising in the field of high-grade steels although the prices are still too high for use in the automobile industry.

Other Ways of Rust-proofing.—Various other means of reducing the effect of rusting on automobiles are being tried. One way is to improve the paint or varnish coatings but these are easily damaged either mechanically or due to the action of oil. The methods of protection by coating the surface with rust resistant metals are quite promising. There are methods of coating with lead, tin, zinc, and aluminum, but the most important is the nickel-plating process. A method has also been developed whereby 10 to 15% chromium may be introduced into the surface. The parts are packed into chromium and heated to high temperatures in an atmosphere of hydrogen. This method has the serious disadvantage that the metal is spoiled by the high heating. A process has been recently developed of plating chromium over nickel-plate and this offers quite promising possibilities.

Chromium Plating for Wear Resistance.—W. Blum¹ reported another method of improving both the rust resistance and the resistance to wear by plating with chromium. Chromium plating gives great hardness and resistance to wear by abrasives. Very favorable results have been obtained by plating the dies used in forming sheet steel and brass, in some cases the life being increased up to 8 times the normal amount by applying a chromium coat less than 0.0005 in. thick. Another strikingly successful application of chromium plating was found in the case of a 9-in. piston rod of a Diesel marine engine. It was found that a chromium-plated layer 0.003 in. thick on the surface of the rod not only resulted in smoother operation and less trouble with lubrication, but also reduced the wear to a remarkable extent. Unplated rods lost about 0.001 in. in diameter for every 5000 miles of service, whereas the chromium-plated rod lost no more than this in 45 000 miles. This piston rod ran in a cast-iron packing with only moderate lubrication.

In a few cases, chromium-plated gears have been found satisfactory. Such cases are, however, mainly with light equipment such as speedometers, etc. In certain cases they have reduced the noise of operation and have also increased the useful life.

In spite of the apparent applicability of chromium plating on machine parts which are subject to wear, its use is still far from being general. This is partly due to the fear that particles of the plate may chip off and serve as abrasives, causing permanent injuries to the mechanism. Although this possibility warrants consideration, the likelihood of such an occurrence is not evident from the meager data available.

The greatest limitation in the use of chromium plating to increase wear resistance is its brittleness, which may cause it to crack and flake. There have been but few successful applications, but these few indicate that with further study many such uses may be developed. When we recall that this process has been in practical use less than three years, there is good reason to believe that, with so many investigators at work, good results may be expected.

¹ W. Blum, Chromium plating for wear resistance, *Machinery*, Feb., 1929.

CHAPTER V

PRINCIPLES FOR THE SELECTION OF STEELS FOR THE VARIOUS PARTS OF AUTOMOBILES

In the present chapter will be described the steels which are commonly used for various parts of the car.

Steel for Gears.—For gears, high strength and wear resistance are required. In Germany carburized gears are mostly used and the kind of steel employed varies according to the magnitude and nature of the stresses likely to be encountered. Table LVIII gives the analysis of various types in the order of the stresses for which they are suitable.

TABLE LVIII

Carbon, Per Cent	Manganese, Per Cent	Chromium, Per Cent	Nickel, Per Cent
Up to 0.15	Up to 0.50	.....	.....
0.10-0.18	0.60-0.80	.....	.....
0.10-0.15	0.40-0.50	0.50-1.0	.....
0.10-0.15	0.40-0.50	.....	1.0-2.0
0.10-0.15	0.40-0.50	.....	2.5-3.5
0.10-0.15	0.40-0.50	0.45-0.55	1.0-1.5
0.10-0.15	0.40-0.50	0.45-0.55	2.0-2.5
0.10-0.15	0.40-0.50	0.70-0.90	2.5-3.0
0.10-0.15	0.40-0.50	0.60-0.80	3.3-3.8
0.10-0.15	0.40-0.50	0.80-1.0	3.8-4.2
0.10-0.15	0.40-0.50	0.80-1.1	4.2-4.8

Straight carbon steels are used for less important parts only. Chromium steel is seldom used in Germany as are also the straight nickel steels.

The chromium-nickel carburizing steels are used most extensively and almost exclusively for transmissions.

Gears.—In France and the United States a straight chromium steel of 0.45 to 0.55% C, 0.5 to 0.8% Mn, and 0.8 to 1.0% Cr is largely used on account of its comparative ease of machining. Those gears are not ground after hardening, as is the practice in Germany, but are smoothed by running them in a special machine before hardening. This steel is quenched from 800 to 850° C. (1470° to 1560° F.) in oil and then drawn to the required strength. If this strength is left sufficiently high the wear resistance will be found to be very good. Occasionally for high-priced cars about 0.2% vanadium is added to this alloy.

Ford uses a molybdenum steel with 0.25 to 0.30% C, 0.5 to 0.7% Mn, 0.7 to 0.9% Cr, 2.6 to 3% Ni, and 0.3 to 0.6% Mo, with the following strength:

Yield point.....	114 000–128 000 lb. per sq. in.
Strength.....	135 000–140 000 lb. per sq. in.
Elongation (gage length 4×diam.).....	19–21%
Reduction.....	55–65%

This steel is easy to forge and permits a high cutting speed which Ford considers the most important feature. Because of this property the molybdenum steel will doubtless find extensive use in the automobile field. For large carburized crown gears chromium-nickel-vanadium steel is used to some extent in America, but in Germany these air-hardening steels are seldom used. The analysis of this steel is: 0.15 to 0.25% carbon, 0.50 to 0.80% manganese, 1.0% chromium, 0.5% nickel, 0.20% vanadium.

Gears should be made from forgings and not cut from rolled or forged bars. The fibers of gears cut from bars are stressed cross-wise and the teeth will break more easily.

Steel for Axles.—Axles should be very tough and are best made from heat-treated steel the strength of which is not greater than 114 000 lb. per sq. in. They have the following composition:

Carbon	Manganese	Chromium	Nickel
0.25–0.35	0.50–0.60	.....	About 2.0
0.25–0.25	0.50–0.60	0.50–0.70	.....
0.25–0.35	0.50–0.60	0.50	About 1.5
0.25–0.35	0.50–0.60	0.50–0.70	2.0–3.0
0.25–0.35	0.50–0.60	0.70–1.0	3.0–3.5

In America front axles are made from straight carbon steel S. A. E. No. 1050 with 0.45 to 0.56% C, 0.5 to 0.8% Mn, 0.045% P, and

0.05% S. The axles are quenched from 820° C. (1570° F.) in water and tempered to 100 000 lb. per sq. in. For front and rear axles straight unheat-treated carbon steel is largely used both in Europe and in America. This steel has the advantage that in case of accident, the axle can be easily straightened. In Europe the specifications for axles are:

Yield point.....	57 000-64 000 lb. per sq. in.
Strength.....	78 000-93 000 lb. per sq. in.
Elongation.....	17-20%
Reduction.....	50-60%

The steels have the following composition: 0.30 to 0.40% C, 0.50 to 0.60% Mn, 0.25% Si, 0.03% P, and 0.03% S. The rear axle runs inside of the rear axle housing, this method of construction being used so that, in case the axle breaks, the rear wheels and axle housing will still support the car. Here a harder heat-treated steel of 155 000 lb. per sq. in. is used:

Carbon	Manganese	Chromium	Nickel
0.30-0.40	0.50-0.60	0.80-1.00	.....
0.30-0.40	0.50-0.60	0.80-1.10	About 3.0

Steel for Steering Spindles, etc.—The steering spindles have to transmit large and sudden loads and therefore should be both strong and very tough. Heat-treated steel is used almost exclusively for these spindles. In Germany, nickel steel, and also to some extent chromium-nickel steel, is used. The strength of these steels after heat treatment should not exceed 120 000 lb. per sq. in. and the analysis is about:

Carbon	Manganese	Chromium	Nickel
0.25-0.35	0.50-0.60	.....	2.0-3.5
0.25-0.35	0.50-0.60	0.50-0.70	2.5-3.5
0.25-0.35	0.50-0.60	0.60-0.90	3.0-4.0

A chromium steel of 0.25 to 0.35% C, 0.5 to 0.6% Mn, 0.5 to 0.8% Cr would be very suitable because of its price and great toughness, but as yet has not found much application. In America S. A. E. steel No. 3275 with 0.4 to 0.5% C, 0.3 to 0.6% Mn, max. 0.04% P, max. 0.04 S, 1.5 to 2% Ni, 0.9 to 1.25% Cr, and heat-treated to 100 000 to 114 000 lb. per sq. in. strength is used for steering spindles.

Heat-treated steel is used for most of the levers on an automobile, the kind of steel used being selected according to the stresses encountered. Hand levers are usually made of straight carbon steel with a strength of 70 000 to 85 000 lb. per sq. in. The clutch, when not made from cast iron, is made from straight carbon steel, as are also the wheel hubs, differential housing, fly-wheel and pedals, unless greater strength or wear resistance is required, in which case non-alloyed carburizing steel is used. Connecting rods are made from high alloy heat-treated steel. When heat-treated to give high enough strength, they are probably superior to rods made from the aluminum alloys because they have greater toughness.

Steel for Wrist-pins.—For wrist-pins a low nickel carburizing steel is sometimes used, but in most cases a straight carbon carburizing steel is sufficient. As an example the following alloys are given:

Carbon	Manganese	Chromium	Nickel
Up to 0.15	0.40–0.50	.....	....
Up to 0.15	0.40–0.50	0.50–1.0	....
Up to 0.15	0.40–0.50	0.50–0.60	1.5

Steel for Shaftings, etc.—In choosing material for shafts it must be considered whether torque only or torque and wear will be encountered. For the shafts of the transmission only carburized steel is suitable and steel containing:

Carbon	Manganese	Chromium	Nickel
Up to 0.15	0.50–0.60	0.50–0.70	2.5
Up to 0.15	0.50–0.60	0.60–0.80	3.0–3.5

is generally used. Other shafts are made from heat-treated high alloy steel up to 155 000 lb. per sq. in. The universal joint is made from carburizing steel, but the shaft itself is made from heat-treated steel. Differential gears are made from high alloy carburizing steel; sheet steel is used for brake housings and wheel rims.

Steel for Crankshafts.—In Germany, crankshafts are chiefly made from high-class steel heat-treated to give 140 000 lb. per sq. in or even 155 000 lb. per sq. in strength. The compositions most commonly used are:

Carbon	Manganese	Chromium	Nickel	
0.25-0.35	0.50-0.60	0.50-0.90	.....	
0.25-0.35	0.50-0.60	0.50-0.70	1.5-2.0	
0.30-0.35	0.50-0.60	0.60-0.80	3.0-3.5	} mostly used
0.30-0.40	0.50-0.60	0.70-1.0	3.0-4.0	

Carburized crankshafts are used to only a slight extent because of the trouble with warping on hardening them. Air and oil hardening steels of the following analysis are used:

Carbon	Manganese	Chromium	Nickel
0.35-0.42	0.50-0.60	1.00-1.50	4.0-4.5 air-hardening
0.35-0.45	0.50-0.60	0.90-1.00	 oil-hardening
0.30-0.40	0.50-0.60	0.70-0.90	1.5-2.0 oil-hardening
0.20-0.25	0.50-0.60	0.80-1.00	About 4.0 oil-hardening

Especially in America crankshafts are made from low alloy steels whose strength seldom exceeds 114 000 lb. per sq. in., and which are easily workable. The standard American crankshaft steel is the S. A. E. steel No. 3435 containing 0.30 to 0.40% C, 0.45 to 0.75% Mn, 2.75 to 3.25% Ni, and 0.6 to 0.95% Cr. This steel is quenched in water and tempered to a strength of 100 000 to 114 000 lb. per sq. in. For truck crankshafts a softer steel containing 0.15 to 0.25% C, 3% Ni, and 0.5% Cr is used. Nitrided crankshafts, although they appear to offer many advantages, are seldom used as yet.

The various analyses that have been given in this book for different parts can not be taken as standard, since the design determines the stresses in the various parts and it is the stress that is the deciding factor in choosing the material. However, it is the hope of the authors that the data given will provide valuable hints in choosing a suitable material.

A comparison of German and other makes shows that, generally speaking, higher alloy steels are used in German cars. In American cars, crankshaft speed over 2000 r.p.m. are avoided on account of the high stresses developed. However, the German tax formula, poorer roads, and also disadvantageous design necessitate the use of higher grade steels. The next problem of the German automobile industry will be to economize in the use of high alloy steels.

CHAPTER VI

STANDARDIZATION OF AUTOMOBILE STEELS

THE AMERICAN STANDARDS ¹

In America the work of standardizing automobile steels was begun by the Association of Licensed Automobile Manufacturers, the predecessor of the National Automobile Chamber of Commerce. In 1900 the work was taken over by the Society of Automotive Engineers, which now publishes the standards annually in the S. A. E. Handbook. The S. A. E. specifications for iron and steel classify the metals according to their chemical composition.

Symbols.—A system of numbers is used for the specifications, the first figure indicating the class to which the steel belongs. The numbers corresponding to different classes of steel are as follows:

Straight carbon steel.....	1
Nickel-carbon steel.....	2
Nickel-chromium steel.....	3
Molybdenum steel.....	4
Chromium steel.....	5
Chromium-vanadium.....	6
Tungsten steel.....	7
Silicon-manganese steel.....	9

In the case of alloy steels, the second figure indicates the approximate percentage of the predominant alloying element. The last two or three figures indicate the approximate carbon content in hundredths of a per cent. Thus: S. A. E. 2340 steel indicates a nickel steel of approximately 3% nickel (3.25 to 3.75) and 0.40% carbon (0.34 to 0.45) and S. A. E. 71360 steel is a

¹ S. A. E. Handbook, 1929, p. 375 ff.

tungsten steel containing about 13% tungsten (12 to 15%) and 0.60 carbon (0.50 to 0.75).

The specifications for the various S. A. E. standard steel are given in the sections of Table LIX.

TABLE LIX.—CHEMICAL COMPOSITIONS OF STEELS *

S. A. E. Standard

CARBON STEELS

S. A. E. Steel No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.
1010	0.05-0.15	0.30-0.60	0.045	0.055
1015	0.10-0.20	0.30-0.60	0.045	0.055
1020	0.15-0.25	0.30-0.60	0.045	0.055
1025	0.20-0.30	0.50-0.80	0.045	0.055
1030	0.25-0.35	0.50-0.80	0.045	0.055
1035	0.30-0.40	0.50-0.80	0.045	0.055
1040	0.35-0.45	0.50-0.80	0.045	0.055
1045	0.40-0.50	0.50-0.80	0.045	0.055
1050	0.45-0.55	0.50-0.80	0.045	0.055
1095	0.90-1.05	0.25-0.50	0.040	0.055
X1315	0.10-0.20	1.25-1.55	0.050	0.085-0.135
1350†	0.45-0.55	0.90-1.20	0.040	0.055
1360†	0.55-0.70	0.90-1.20	0.040	0.055

* From the report of the Iron and Steel Division, adopted by the Society June, 1912. Last revision, August, 1928.

† The silicon content for steels 1350 and 1360 shall not exceed 0.30%.

SCREW STOCK

S. A. E. Steel No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Range
1112	0.08-0.16	0.60-0.80	0.09-0.13	0.08-0.155
1120	0.15-0.25	0.60-0.90	Max. 0.06	0.08-0.155

TABLE LIX.—CHEMICAL COMPOSITIONS OF STEELS—*Continued*

STEEL CASTINGS

S. A. E. Steel No.	Carbon	Phosphorus, Max.	Sulphur, Max.
1235	As required by physical properties.	0.05	0.055

NICKEL STEELS

S. A. E. Steel No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Nickel Range
*2015	0.10-0.20	0.30-0.60	0.04	0.05	0.40-0.60
*2115	0.10-0.20	0.30-0.60	0.04	0.05	1.25-1.75
2315	0.10-0.20	0.30-0.60	0.04	0.05	3.25-3.75
2320	0.15-0.25	0.30-0.60	0.04	0.05	3.25-3.75
2330	0.25-0.35	0.50-0.80	0.04	0.05	3.25-3.75
2335	0.30-0.40	0.50-0.80	0.04	0.05	3.25-3.75
2340	0.35-0.45	0.50-0.80	0.04	0.05	3.25-3.75
2345	0.40-0.50	0.50-0.80	0.04	0.05	3.25-3.75
2350	0.45-0.55	0.50-0.80	0.04	0.05	3.25-3.75
2512	max. 0.17	0.30-0.60	0.04	0.05	4.75-5.25

* Silicon range 0.15-0.30.

MOLYBDENUM STEELS

S. A. E. Steel No.	Carbon Range	Manga- nese Range	Phos- phorus, Max.	Sul- phur, Max.	Chro- mium Range	Nickel Range	Molyb- denum Range
4130	0.25-0.35	0.40-0.70	0.04	0.05	0.50-0.80	.....	0.15-0.25
4140	0.35-0.45	0.40-0.70	0.04	0.05	0.80-1.10	.....	0.15-0.25
4150	0.45-0.55	0.40-0.70	0.04	0.05	0.80-1.10	.....	0.15-0.25
4615	0.10-0.20	0.30-0.60	0.04	0.05	.....	1.50-2.00	0.20-0.30

TABLE LIX.—CHEMICAL COMPOSITIONS OF STEELS—*Continued*

NICKEL-CHROMIUM STEELS

S. A. E. Steel No.	Carbon Range	Manganese Range	Phos- phorus, Max.	Sulphur, Max.	Nickel Range	Chromium Range
3115	0.10-0.20	0.30-0.60	0.04	0.05	1.00-1.50	0.45-0.75
3120	0.15-0.25	0.30-0.60	0.04	0.05	1.00-1.50	0.45-0.75
3125	0.20-0.30	0.50-0.80	0.04	0.05	1.00-1.50	0.45-0.75
3130	0.25-0.35	0.50-0.80	0.04	0.05	1.00-1.50	0.45-0.75
3135	0.30-0.40	0.50-0.80	0.04	0.05	1.00-1.50	0.45-0.75
3140	0.35-0.45	0.50-0.80	0.04	0.05	1.00-1.50	0.45-0.75
3215	0.10-0.20	0.30-0.60	0.04	0.045	1.50-2.00	0.90-1.25
3220	0.15-0.25	0.30-0.60	0.04	0.045	1.50-2.00	0.90-1.25
3230	0.25-0.35	0.30-0.60	0.04	0.045	1.50-2.00	0.90-1.25
3240	0.35-0.45	0.30-0.60	0.04	0.045	1.50-2.00	0.90-1.25
3245	0.40-0.50	0.30-0.60	0.04	0.045	1.50-2.00	0.90-1.25
3250	0.45-0.55	0.30-0.60	0.04	0.045	1.50-2.00	0.90-1.25
3312	max. 0.17	0.30-0.60	0.04	0.045	3.25-3.75	1.25-1.75
3325	0.20-0.30	0.30-0.60	0.04	0.045	3.25-3.75	1.25-1.75
3335	0.30-0.40	0.30-0.60	0.04	0.045	3.25-3.75	1.25-1.75
3340	0.35-0.45	0.30-0.60	0.04	0.045	3.25-3.75	1.25-1.75
3415	0.10-0.20	0.30-0.60	0.04	0.045	2.75-3.25	0.60-0.95
3435	0.30-0.40	0.30-0.60	0.04	0.045	2.75-3.25	0.60-0.95
3450	0.45-0.55	0.30-0.60	0.04	0.045	2.75-3.25	0.60-0.95

CHROMIUM STEELS

S. A. E. Steel No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Chromium, Range
5120	0.15-0.25	0.30-0.60	0.04	0.05	0.60-0.90
5140	0.35-0.45	0.50-0.80	0.04	0.05	0.80-1.10
5150	0.45-0.55	0.50-0.80	0.04	0.05	0.80-1.10
52100	0.95-1.10	0.20-0.50	0.03	0.035	1.20-1.50

TABLE LIX.—CHEMICAL COMPOSITIONS OF STEELS—*Continued*

CHROMIUM-VANADIUM STEELS

S. A. E. Steel No.	Carbon Range	Manga- nese Range	Phos- phorus, Max.	Sul- phur, Max.	Chromium Range	Vanadium	
						Min.	De- sired
6120	0.15-0.25	0.30-0.60	0.04	0.045	0.80-1.10	0.15	0.18
6125	0.20-0.30	0.50-0.80	0.04	0.045	0.80-1.10	0.15	0.18
6130	0.25-0.35	0.50-0.80	0.04	0.045	0.80-1.10	0.15	0.18
6135	0.30-0.40	0.50-0.80	0.04	0.045	0.80-1.10	0.15	0.18
6140	0.35-0.45	0.50-0.80	0.04	0.045	0.80-1.10	0.15	0.18
6145	0.40-0.50	0.50-0.80	0.04	0.045	0.80-1.10	0.15	0.18
6150	0.45-0.55	0.50-0.80	0.04	0.045	0.80-1.10	0.15	0.18
6195	0.90-1.05	0.20-0.45	0.03	0.035	0.80-1.10	0.15	0.18

TUNGSTEN STEELS

S. A. E. Steel No.	Carbon Range	Man- ganese, Max.	Phos- phorus, Max.	Sul- phur, Max.	Chromium Range	Tungsten Range
71360	0.50-0.70	0.30	0.035	0.04	3.00-4.00	12.00-15.00
71660	0.50-0.70	0.30	0.035	0.04	3.00-4.00	15.00-18.00
7260	0.50-0.70	0.30	0.035	0.04	0.50-1.00	1.50- 2.00

SILICO-MANGANESE STEELS

S. A. E. Steel No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Silicon Range
9250	0.45-0.55	0.60-0.90	0.045	0.05	1.80-2.20
9260	0.55-0.65	0.60-0.90	0.045	0.05	1.80-2.20

Heat-treat Charts.—For the heat treatment of the steels, charts have been prepared which show properties of the steels corresponding to various drawing temperatures. It will be remembered from the explanations in the chapter on heat treatment that those values are only approximate since such factors as size, depth of hardening, and time of tempering also influence the properties.

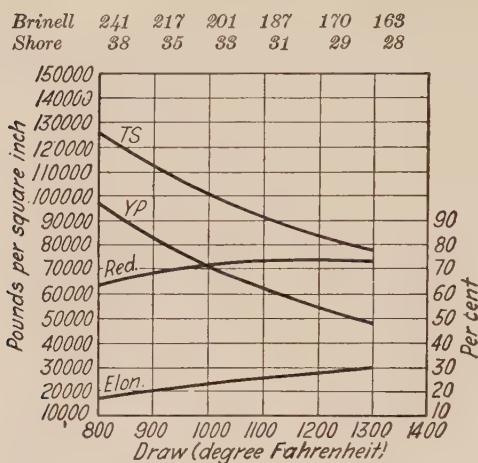


FIG. 50.—Properties of American steel S.A.E. 3120.
Hardened at 1570 – 1625° F. in Oil

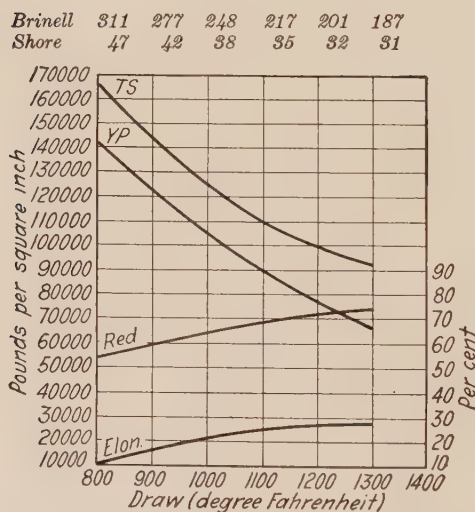


FIG. 51.—Properties of American steel S.A.E. 3130.
Hardened at 1500 – 1550° F. in Water

Brinell	331	302	269	248	223	217
Shore	49	45	41	38	35	33

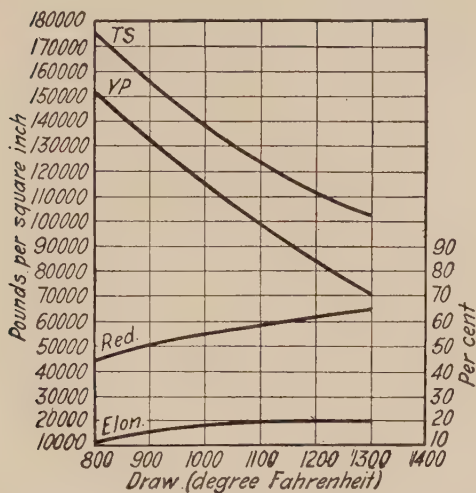


FIG. 52.—Properties of American steel S.A.E. 3140.

Hardened at 1470–1525° F. in Oil

Brinell	311	277	248	223	174	154
Shore	46	42	38	36	32	29

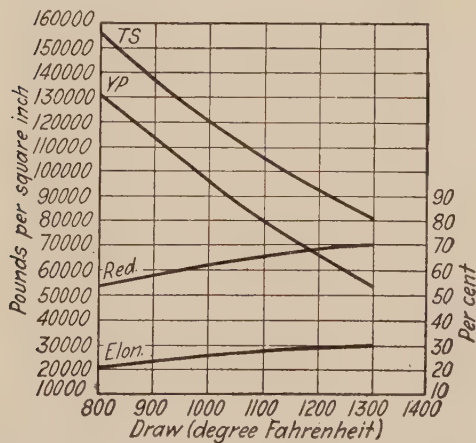


FIG. 53.—Properties of American steel S.A.E. 3220.

Hardened at 1500–1600° F. in Oil

Brinell	388	341	321	285	255	229
Shore	58	51	47	42	39	35

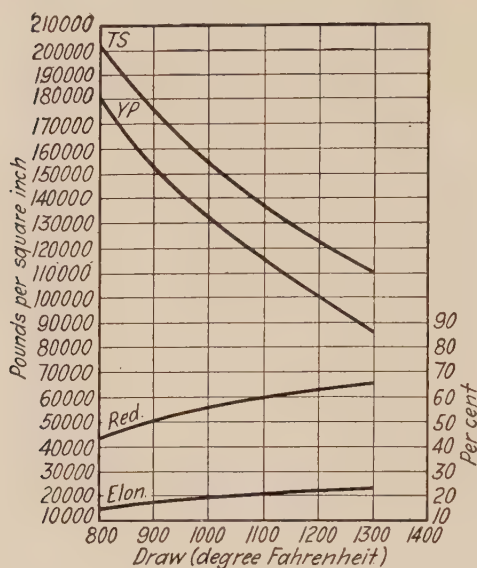


FIG. 54.—Properties of American steel S.A.E. 3240.
Hardened at 1475–1525° F. in Oil

Brinell	415	375	331	293	269	241
Shore	61	55	49	44	41	38

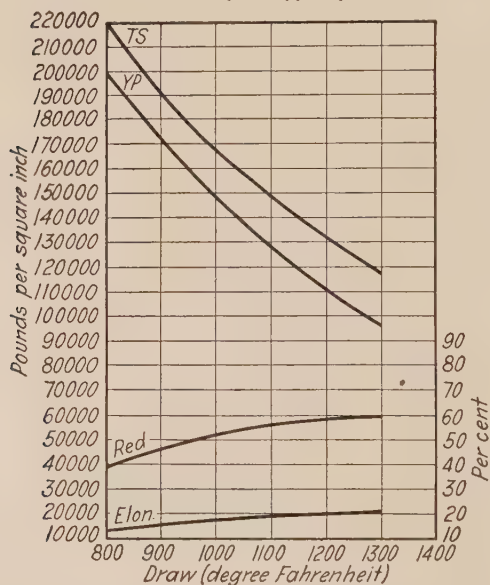


FIG. 55.—Properties of American steel S.A.E. 3250.
Hardened at 1425–1475° F. in Oil

Brinell	352	302	269	248	229
Shore	50	45	42	39	36

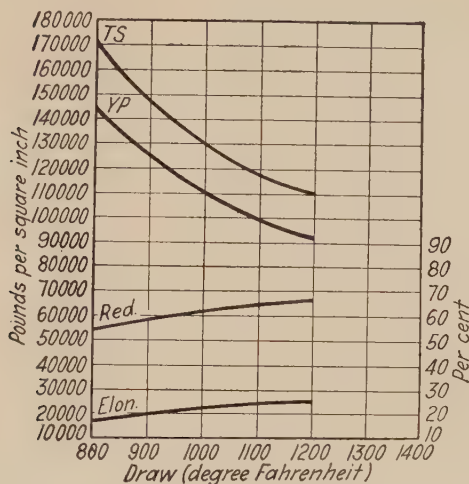


FIG. 56.—Properties of American steel S.A.E. 3325.

Hardened at 1475–1525° F. in Oil

Brinell	375	331	302	272	241
Shore	56	49	45	41	38

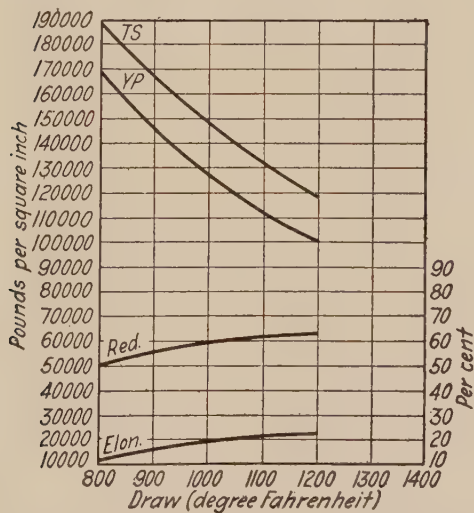


FIG. 57.—Properties of American steel S.A.E. 3335.

Hardened at 1425–1475° F. in Oil

Brinell	341	311	285	262	229
Shore	58	52	46	43	38

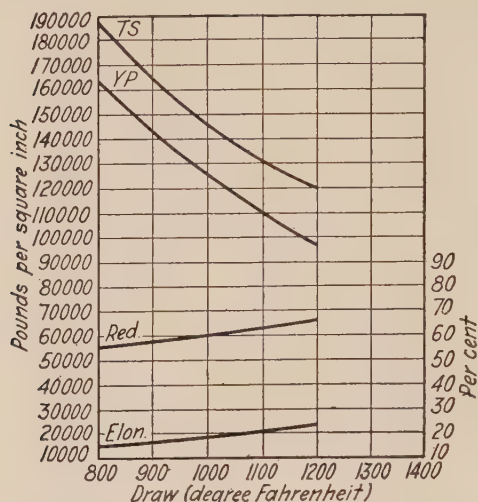


FIG. 58.—Properties of American steel S.A.E. 3435.
Hardened at 1425–1475° F. in Oil

Brinell	375	352	321	293	269
Shore	68	58	52	47	42

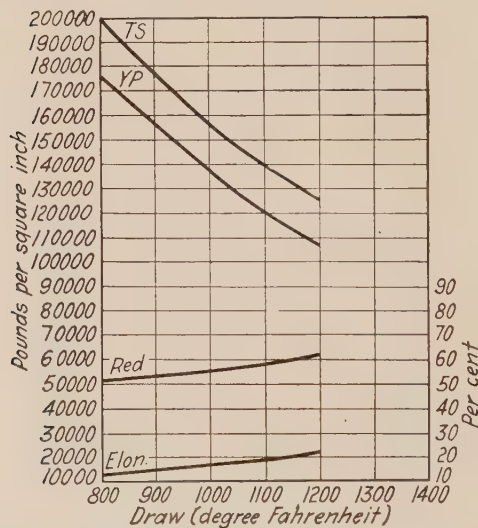


FIG. 59.—Properties of American steel S.A.E. 3450.
Hardened at 1400–1455° F. in Oil

THE GERMAN STANDARDS

The economical manufacture of steel and the tendency to reduce the price of certain parts as much as possible brought about in Germany as well as other countries the standardization and limitation of types. The Deutsche Industrie Normen DIN, (German Industrial Standards) had been established but they covered the field of straight carbon steel only. They were of considerable value, particularly for the purchaser's inspection, since they established standards for the testing of materials. It was realized that analysis alone was not a sufficient basis for specifications and left open a number of possible faults, but the DIN standards made the properties reasonably reliable. The viewpoints on material standardization in Germany and in other countries were well presented by W. Eilander and W. Oertel.¹

Symbols.—The German DIN sheets give, between the number 1600 and 1699, iron and steel products according to the following classification:

1600–1609	General testing of materials
1610–1619	Soft steel. Common machinery steel
1620–1629	Soft steel. Sheet metal. Pipes
1630–1639	Rail road track material
1640–1649	Material for railroad vehicles
1650–1659	Miscellaneous
1660–1669	Steel. Special steel
1670–1679	Tool steel
1680–1689	Steel castings
1690–1699	Cast iron

The editing of the standard sheets has not yet gone very far and large gaps remain to be filled. However, there has already been established a uniform system of designating different steels, and specifications for the testing and inspection of material are established also.

The three parts of the designation for different classes of iron and steel are:

1. The first symbol is a group of letters whose meaning is as follows:

St for steel	Ge for cast iron
Stg. for steel casting	Te for malleable iron

¹ *Mitt. d. Fachnormen-Ausschusses d. Kraft Fahrzeug-Industrie*, Heft 10, Dec. 15, 1926.

2. The second symbol consists of two figures indicating the minimum strength, or when preceded by the letter C the average carbon content is indicated. For material without any special guaranty the figures 00 are used.
3. The third symbol consists of two figures giving the number of the standard sheet.

For example:

St 37,34 stands for a steel with minimum strength of 37 kg. per mm.² as specified on DIN sheet No. 1634; and

St C 25,61 stands for a steel with an average carbon content of 0.25% as specified on DIN sheet No. 1661.

In ordering steel the following sequence is followed: kind of material, dimensions, brand, DIN number, and condition in which the steel is to be delivered. A letter may be used before the DIN number to indicate the method of manufacture, thus, B means Bessemer; M, open hearth; Th, Thomas; T, crucible; and E, electric furnace. For instance, if the order specifies: case-hardening steel St C 1061 M DIN 1661 annealed, then a case-hardening steel with 0.10% carbon made in an open-hearth furnace, conforming to DIN 1661 and delivered in an annealed condition is wanted.

The accompanying tables give some makes with their properties conforming to DIN 1611 B straight carbon steel. Neither phosphorus nor sulphur should exceed 0.06% and the two together should be below 0.10%. The relatively high phosphorus and sulphur render these steels unsuitable for automobile use since their quality and uniformity would be too poor.

TABLE LX.—DIN 1611 B STRAIGHT CARBON STEEL

Designation	Strength		Elongation: Minimum Gage Length		Carbon, Per Cent	Quality; Suitable for
	Kg. per Sq. Mm.	1000 Lb. per Sq. In.	10 × Diam., Per Cent	5 × Diam., Per Cent		
St 34.11	34-42	48-60	25	30	0.12	Case-hardening; fire-welding
St 42.11	42-50	60-71	20	24	0.25	Case-hardening for hard core; hard to fire-weld
St 50.11	50-60	71-85	18	22	0.35	Not for case-hardening; not for fire-welding; little hardenable
St 60.11	60-70	85-100	14	17	0.45	Hardenable; heat-treat.
St 70.11	70-85	100-120	10	12	0.60	Hardenable; heat-treat.

The information in DIN 1661 regarding straight carbon carburizing and heat treating steel is interesting. Phosphorus and sulphur must each be max. 0.04% and together not more than 0.07%. Table LXI and LXII give the specifications.

TABLE LXI.—DIN 1661 STRAIGHT CARBON CASE-HARDENING STEEL

Designation	Yield Point, 1000 Lb. per Sq. In.	Strength, 1000 Lb. per Sq. In.	Elongation: Minimum Gage Length		Carbon, Per Cent	Manganese, Per Cent Max.	Silicon, Per Cent Min.	
			10 × Diam., Per Cent	5 × Diam., Per Cent				
St C 10.61	30	40	25	30	0.06–0.13	0.50	0.35	{ Annealed state
St C 16.61	33	60	23	28	0.13–0.20	0.40	0.35	

TABLE LXII.—DIN 1661 STRAIGHT CARBON HEAT-TREATING STEELS

Designation	State	Strength, 1000 Lb. per Sq. In.	Yield Point, 1000 Lb. per Sq. In.	Elongation: Minimum Gage Length		Carbon	Manganese, Max.	Silicon, Min.
				10 × Diam., Per Cent	5 × Diam., Per Cent			
St C 25.61	Annealed	60–71	34	22	27	0.25	0.80	0.35
	Heat treated	67–78	39	20	24	.....	.....	.....
St C 35.61	Annealed	71–85	39	19	23	0.35	0.80	0.35
	Heat treated	78–93	47	18	22	.....	.....	.....
St C 45.61	Annealed	85–100	48	16	19	0.45	0.80	0.35
	Heat treated	93–107	55	15	18	.....	.....	.....
St C 60.61	Annealed	100–121	57	13	15	0.60	0.80	0.35
	Heat treated	107–128	64	12	14	.....	.....	.....

Standards for Alloyed Steel.—High grade steels were standardized as given in Table LXIII.

It is very fortunate that the large number of steel brands has been reduced. It is really possible to get along with two kinds of case-hardening steel and two kinds of heat-treating steel. This reduces the stock of steel which must be kept on hand. Table LXIV has been prepared to give a comparison of the new standard steel with the brands formerly made by various companies. This table will prove useful during the adjustment period, but can not pretend to be finally correct or complete.

TABLE LXIII.—GERMAN STANDARDS FOR ALLOYED STEELS

E = Case-hardening steels. V = Heat-treated steels.

Purity.—Sulphur and phosphorus not more than 0.035% each, together not more than 0.06%. For acid steel, phosphorus and sulphur not more than 0.045% each, and not more than 0.075% together.

Designation	Strength, 1000 Lb. per Sq. In.		Yield Point, Percentage of Strength	Elongation: Gauge Length 10× Diam., Per Cent	Brinell Strength, 1000 Lb. per Sq. In.	Analysis			
	Heat-treated	Hardened in Core				Carbon, Per Cent	Nickel, Per Cent	Chromium, Per Cent	Manganese, Per Cent
En 15		85-114 water	70	15- 8	≤ 78	0.09-0.18	1.5±0.25	0.30 max.	≤ 0.5
ECN 35		128-170 oil	70	12- 6	≤ 100		3.5±0.25	0.75±0.2	
VCN 15	tough 93-114		70	16-12	≤ 100		1.5±0.25	0.5±0.2	≤ 0.35
VCN 25	tough 100-121 hard 121-142		70	14-10 12- 8	≤ 100	0.25-0.40	2.5±0.25		0.4-0.8
VCN 35	tough 107-128 hard 128-150		75	14-10 12- 8	≤ 114		3.5±0.25	0.75±0.2	
Guides for Peak Steels									
ECN 45						0.09-0.18			≤ 0.5
VCN 45						≈ 0.3	≈ 4.5	≥ 0.8	≤ 0.35 0.4-0.8

TABLE LXIV.—COMPARISON OF BRANDS OF VARIOUS GERMAN STEEL COMPANIES WITH NEW STANDARD DESIGNATION

Case-hardening Steels						Heat-treating Steels					
EN 15	EN 25	ENC 25	ENC 35	ENC 45	VN 15	VN 25	VN 35	VNC 25	VNC 25	VNC 45	
1-2	2-3	2-3	3-4	4-5	1-2	2-3	3-4	2-3	3-4	4-5	
	NO 30	NCE	NCO 1	NCO 3	BNA	NA 3		NCA 10		NCO 4	
		E 53	E 724	LWZ	HBN				KWD	LWD	
N 2	NSVa	NC 15	NC 1	NC 4	N 2 H	NSVah	N3H	KNCV	NKHV	NKHF	
				LWZ							
NBV2W	NBVW	CNBV 2	CNVE	CNBV/Z	NBV	NVB 3		CNBV	CNBVK	CNVBL	
ENA	3 NW	ESprima		ES extra	Ni	3 NM			Extra PA		
	NW					NH				ZKL	
	NW 3	NWC	ZR	ZRH		NH 3	NH 3	NHC	NH3Z	ZK	
		ECN 1		ECN 5	VN 2						
Ni 2	Ni 3	NiC 3	NiC 4	NiC 5	NV				CNV		
		EF 350	EF 58	EF 59				EF 29			
	N 3a	CNS 5	CNS 4	CNS 2	C 46			EF 38	EF 55	EF 7	
Ty 1 W	Ty 3 W	TEM	TEJ	TEJ					CNK 2	CNK 1	
REN 2	REN 3		RAE 3	RAE 5		Ty 3 M		TBOS	CNS		
	EN 3		LM 1	ENC 4	RN 2	RN 3		RAN 3	RAN 4		
			SCN 40								
	EN 5 W										
EN 1 W	EN 3 W	NW 1	NW 3	EE							

Designation	Name of Company										
	Nickel										
Becker Stahlw											
Berg. Stahlind											
Bismarckhütte											
Bischoff											
Bochum. Verein.											
Böhler											
Stahlw. Crefeld											
Döhlener Guss-stw.											
Eicken & Co.											
Krupp A.-G											
Lindenber.											
Poldihütte											
Röchling											
Schoeller											
Siegen Solingen											
Steyrische											
Guss-stahlwerke.											

Name of Company

CHAPTER VII

FAILURES¹

In this section are shown some instructive pictures of a number of fractures with short notes on the characteristics or cause of each failure.

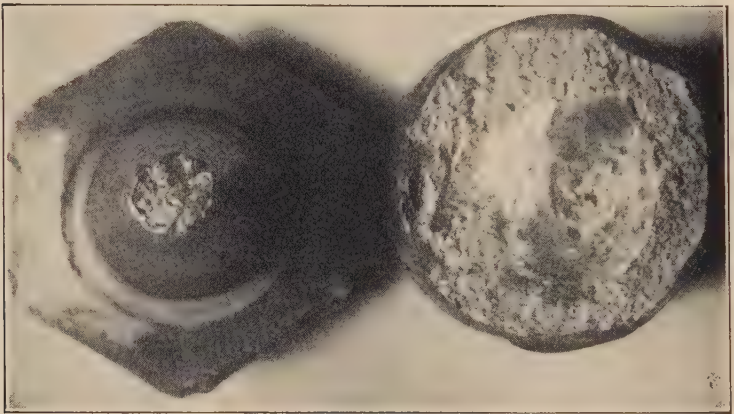


FIG. 60.—Broken bolts. The one on the left shows the great reduction characteristic of deformation breaks. The one on the right hand is a plain fracture almost without deformation.

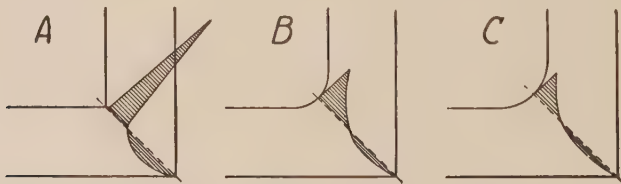


FIG. 61.—Stresses are highest in sharp corners (A); a round fillet reduces the stress, while the section as well as the resistance is increased (B and C).

¹ M. v. Schwarz, *Zeitschrift d. Bayr. Rev. Ver.*, 1927, Nr. 5/6.

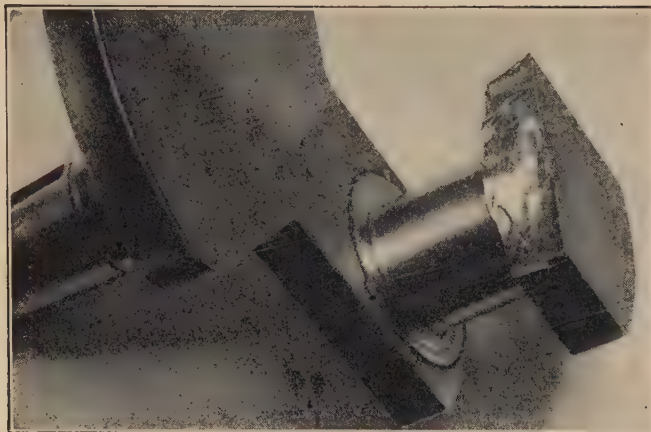


FIG. 62.—Fatigue break of a motorcycle crankshaft starting at corner which had too small a radius.



FIG. 63.—Fatigue break by torsion, crankshaft of a bus engine; break was favored by too small a radius.



FIG. 64.—Fatigue break of axle of a motor cycle, started on the sharp corner of the keyway.



FIG. 65.—Fatigue break of steering spindle of a motor car.

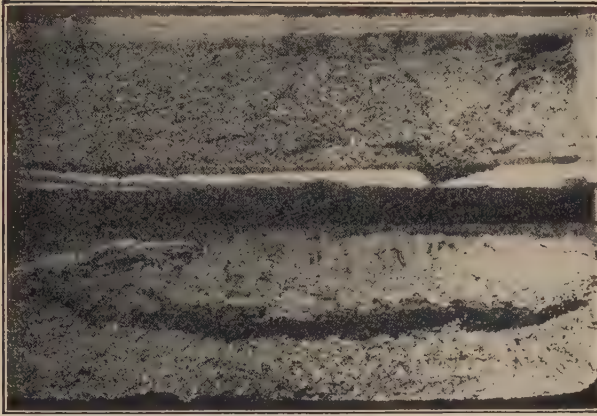


FIG. 66.—Fracture of flat rolled steel: Top—broken by sudden blow; bottom—broken by twice bending forward and backward; this makes the center look as if made from a different material.

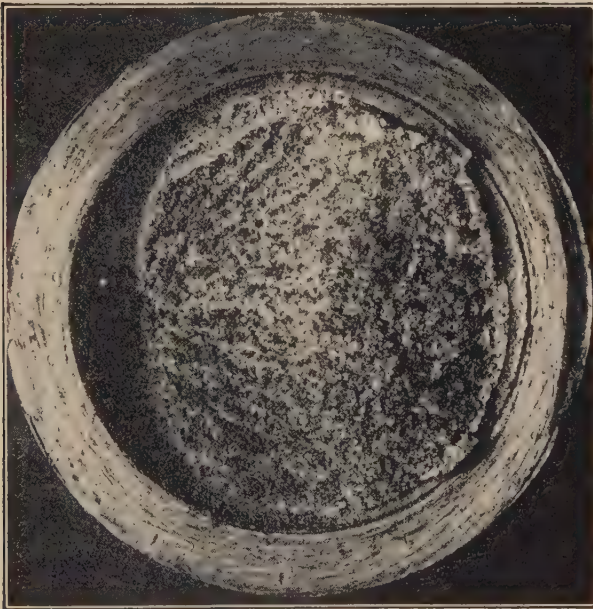


FIG. 67.—Fatigue break from axle of a motor car. A sudden change in section without any radius was the reason.

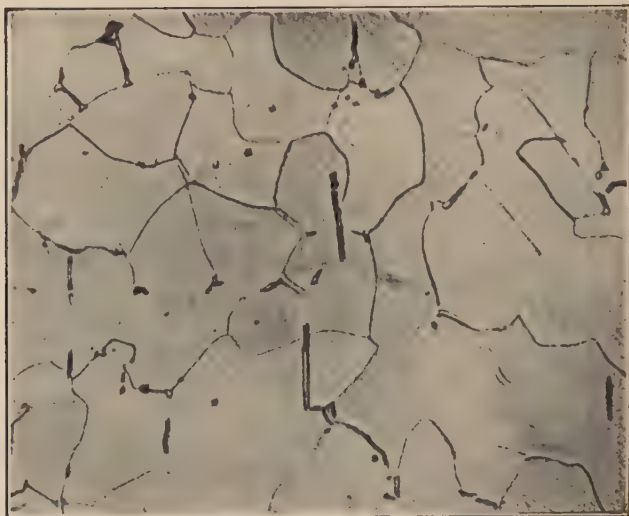


FIG. 68.—The polished longitudinal section $\frac{3}{8}$ in. from the rupture (Fig. 67) shows less carbon than the center, and some slags. The center showed considerable segregation.

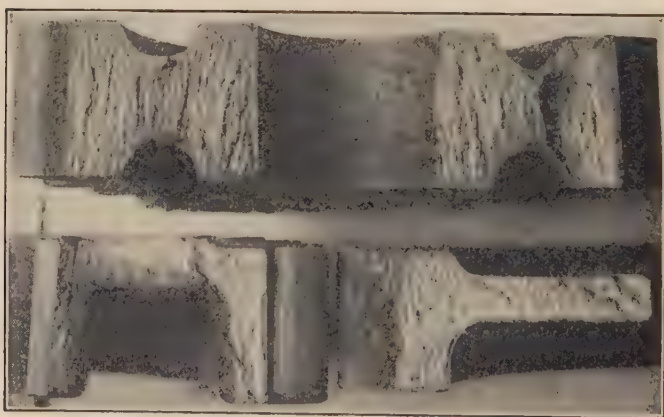


FIG. 69.—Purposely broken gears from chromium-nickel case-hardening steel: Top—straight fibers show that the gear was cut from a bar; bottom—bent fibers show the forged gear.

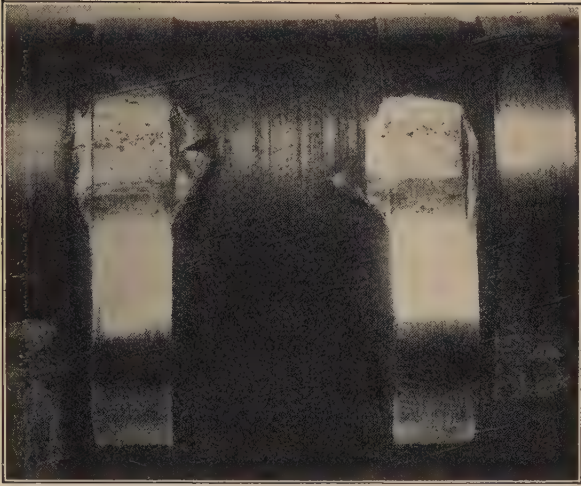


FIG. 70.—Camshaft of French automobile, failed after short service due to a too small case-hardening depth.

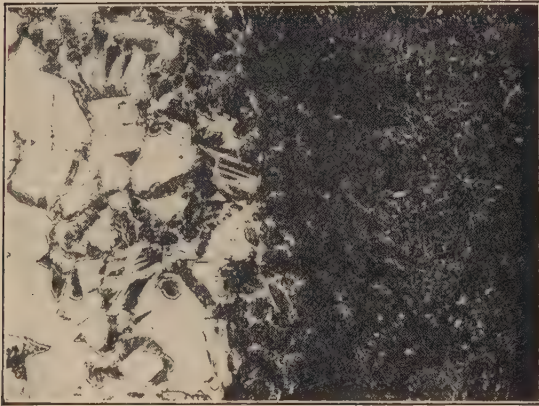


FIG. 71.—Etched section of Fig. 70: Hard zone appears dark on the right side.

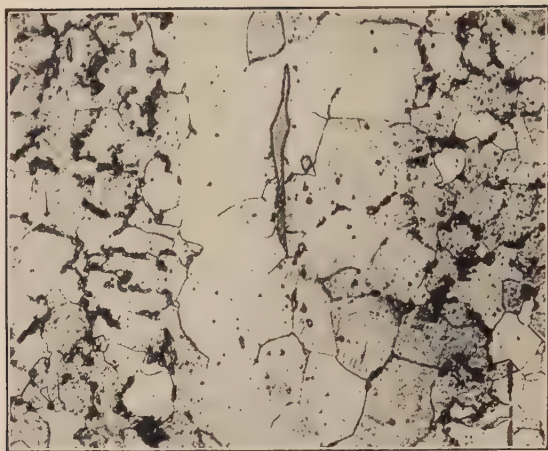


FIG. 72.—Longitudinal section of Fig. 70-71: Coarse grain with many sulphurous slags, poor steel (0.11 per cent C, 0.64 per cent Mn, 0.013 per cent Si, 0.133 per cent P, 0.085 per cent S).



FIG. 73.—Grinding marks on a spring caused breakage through notching effect.

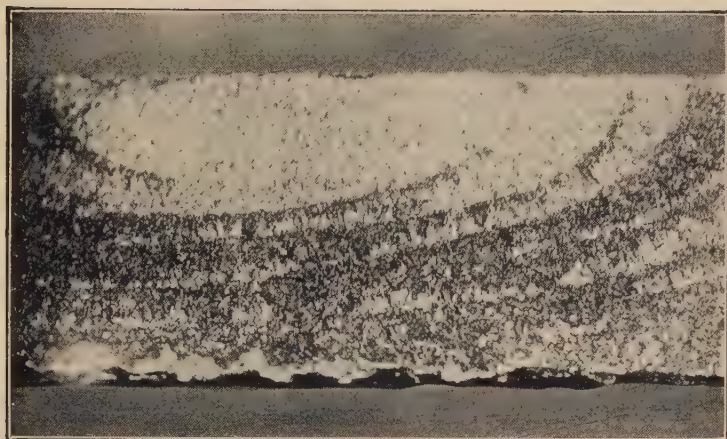


FIG. 74.—Rupture of the spring of Fig. 73.



FIG. 75.—Purposely broken part of the spring Fig. 73-74 shows above starts of breaks, darkened with oil. These beginning breaks were caused by scratches.

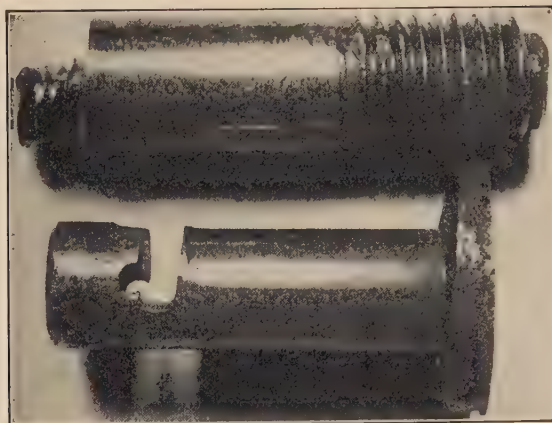


FIG. 76.—Bolts from a motorcycle, worn through by loose washers.

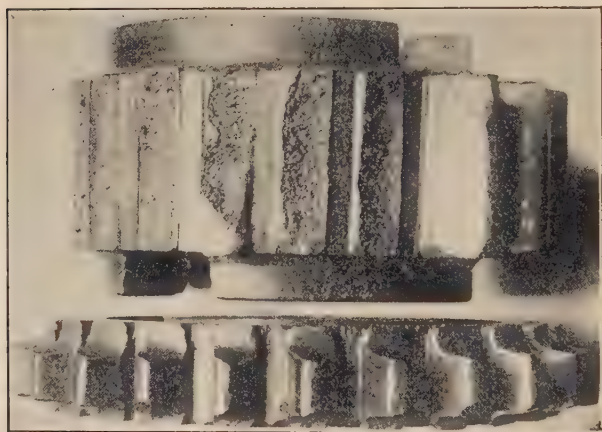


FIG. 77.—Top-gear cut off from a bar. Teeth broken. Bottom-gear forged. Teeth after 12 years' service worn off.

CHAPTER VIII

STEEL ANALYSIS OF AUTOMOBILE PARTS

The tables given in this chapter contain steel analysis of various automobile parts. Thanks to the cooperation of some of the leading manufacturing plants it was possible to include up-to-date information on the latest models. It will be remembered from the explanation in Chapter V that the deciding factor in choosing material is the stress. Since the stress is determined by the design of the part, the data given in the following tables are not readily comparable. They will, however, furnish interesting and valuable information if used with proper discretion.

Deviations in the strength as given in these tables and in those given in the book previously are caused by the fact that all data in the book refer to a uniform medium section, while the data in the following tables refer to the particular parts, which of course vary largely in section. Especially in the case of heat-treated and carburized material the strength is largely depending upon the dimensions of the part.

Name of Company	Table
Ford Motor Company, Detroit, Mich.....	LXV
Chevrolet Motor Car Company, Detroit, Mich.....	LXVI
Cadillac Motor Car Company, Detroit, Mich.....	LXVII
Daimler Benz Aktiengesellschaft, Stuttgart, Germany.....	LXVIII
Horchwerke Aktiengesellschaft, Zwickau, Germany.....	LXIX
Nationale Automobil Gesellschaft, Berlin, Germany.....	LXX
N. S. U. Vereinigte Fahrzeugwerke A. G., Neckarsulm, Germany	LXXXI
Wanderer Werke, Schöna, Germany.....	LXXXII
Steyrwerke A. G., Steyr, Austria.....	LXXXIII
Société Anonyme des Usines Renault, Billancourt, France.....	LXXIV
Société Anonyme des Automobiles Peugeot, Paris, France.....	LXXV
Fiat Societa Anonima, Torino, Italy.....	LXXXVI
Morris Motors Ltd., Cowley, Oxford, Great Britain.....	LXXVII

TABLE LXV.—AUTOMOBILE PARTS STEEL ANALYSIS. FORD MOTOR COMPANY—MODEL A
Courtesy of Ford Motor Company, Detroit, Mich.

Type of Steel	Carbon	Manganese	Chromium	Vanadium	Silicon	Phosphorus	Sulphur	Name of Part
A.....	0.17-0.22	0.60-0.75	0.65-0.80	Vanadium 0.12-0.15	0.10-0.15	0.03 max.	0.04 max.	Rear axle driving pinion, front wheel spindle bolt
AX.....	0.18-0.22	0.65-0.75	0.80-0.95	.....	0.10-0.20	0.03 max.	0.04 max.	Steering worm, front wheel bearing rollers
AA.....	0.26-0.30	0.65-0.80	0.80-1.00	.....	0.10-0.20	0.03 max.	0.04 max.	Front axle, connecting rod
AAA.....	0.30-0.35	0.65-0.80	0.90-1.10	.....	0.10-0.20	0.03 max.	0.04 max.	Dual high planet and sun gears
AAAH.....	0.35-0.38	0.65-0.80	0.90-1.10	.....	0.10-0.20	0.03 max.	0.04 max.	Transmission main drive gear, transmission main drive shaft
AAAAL.....	0.38-0.42	0.65-0.80	0.90-1.10	.....	0.10-0.20	0.03 max.	0.04 max.	Rear axle driving gear drive shafts
AAAA.....	0.42-0.47	0.70-0.90	0.85-1.10	.....	0.10-0.20	0.03 max.	0.04 max.	Tractor and Lincoln transmission gears
AAAAA.....	0.48-0.52	0.70-0.90	0.85-1.10	.....	0.10-0.20	0.03 max.	0.04 max.	Tractor and Lincoln transmission gears
AA select.....	0.28-0.32	0.65-0.80	0.80-1.00	.....	0.10-0.20	0.03 max.	0.04 max.	Spindle arm
AAA select.....	0.32-0.35	0.65-0.80	0.90-1.10	.....	0.10-0.20	0.03 max.	0.04 max.	T 12 pump shaft
Armature steel.....	0.05 max.	0.30 max.	.....	.....	0.12-0.28	0.03 max.	0.04 max.	Starter armature lamination
B.....	0.95-1.05	0.20-0.30	0.40-0.50	.....	0.20-0.30	0.03 max.	0.04 max.	Steel balls (small)
BB.....	0.95-1.05	0.20-0.30	0.90-1.10	.....	0.20-0.30	0.03 max.	0.04 max.	Large balls, small races
BBB.....	0.95-1.05	0.30-0.40	1.25-1.50	.....	0.20-0.30	0.03 max.	0.04 max.	Large races
No. 1 Bessemer.....	0.09-0.13	0.70-0.90	.....	.....	.....	0.09-0.13	0.08-0.12	Special castle nut
C key stock.....	0.30-0.40	0.50-0.80	.....	.....	0.10-0.20	0.05 max.	0.05 max.	Woodruff keys
D.....	0.45-0.52	0.80-0.95	1.00-1.20	.....	0.10-0.20	0.03 max.	0.04 max.	Rear spring
DD.....	0.48-0.52	0.80-0.95	1.00-1.20	.....	0.10-0.20	0.03 max.	0.04 max.	Front spring
Die block ajax.....	0.60-0.75	0.30-0.40	3.25-3.75	.....	0.10-0.20	0.03 max.	0.04 max.	.....
Die block hammer.....	0.47-0.55	0.50-0.60	0.60-0.75	Nickel 1.50-1.75	0.10-0.20	0.03 max.	0.04 max.	Rad. rod yoke, rear wheel hub, drive shaft, steering gear arm
E.....	0.27-0.35	0.70-0.90	.....	.....	0.07-0.15	0.04 max.	0.05 max.	.....
EE.....	0.35-0.40	0.70-0.90	.....	.....	0.07-0.15	0.03 max.	0.05 max.	Crankshaft

EEE.....	0.40-0.45 0.05 max.	0.70-0.90 0.30 max.	.....	.....	0.07-0.15	0.03 max.	0.05 max.	Camshaft, rear axle shaft
Electric steel.....	.....	.....	.....	.....	0.90-1.20	0.03 max.	0.03 max.	Generator armature lami- nation
Ford special high speed..	0.60-0.70	0.25-0.35	3.75-4.25	Vanadium 0.90- 1.10, tungsten 17 0-18.0	0.20-0.30	0.03 max.	0.04 max.	
G.....	0.08-0.15	0.30-0.45	.....	.....	0.07-0.15	0.03 max.	0.05 max.	Steering column, support lower to upper screw, rivets, bolts
GG.....	0.15-0.20	0.30-0.45	.....	.....	0.07-0.15	0.04 max.	0.05 max.	Steeringworm, rear driving pinion bearing cup, rear brake cam
H.....	0.27-0.37	0.45-0.60	.....	.....	0.07-0.15	0.04 max.	0.05 max.	Coupling shaft housing end
Rustless iron.....	0.05-0.10	0.30-0.45	16.00-18.00	.....	0.50-0.75	0.04 max.	0.05 max.	Radiator shell, wheel hub shell cup
K.....	0.10 max.	0.45 max.	.....	.....	.....	0.04 max.	0.05 max.	Generator pole pieces
L.....	0.23-0.30	0.35-0.50	.....	.....	.....	0.04 max.	0.05 max.	Frame members, torque tube
Low carbon, open-hearth.	0.08-0.15	0.35-0.50	.....	.....	.....	0.04 max.	0.05 max.	Fenders, door panel
Magnet.....	0.82-0.90	0.30-0.45	2.25-2.60	.....	0.25-0.40	0.03 max.	0.04 max.	T magnet, speedometer magnets
N.....	0.10-0.15	0.25-0.40	0.25-0.35	.....	0.10-0.20	0.03 max.	0.04 max.	Piston pins
Nickel key stock.....	0.25-0.35	0.50-0.80	.....	Nickel 3.25-3.75	0.10-0.20	0.04 max.	0.045 max.	T differential gear keys
RR.....	0.95-1.05	0.20-0.35	0.10 max.	.....	0.15-0.25	0.025 max.	0.03 max.	T commutator roller, T spindle 4 speed trans- mission pins
Chrome non shrink.....	1.45-1.60	0.25-0.35	11.00-12.00	Vanadium 0.20- 0.25, Molyb- denum, 0.70- 0.80	0.20-0.40	0.03 max.	0.04 max.	
S.....	0.60-0.70	0.70-0.85	.....	.....	0.15-0.20	0.03 max.	0.04 max.	Valve springs
SS.....	0.80-0.95	0.30-0.45	.....	.....	0.10-0.20	0.03 max.	0.04 max.	Bumper bars
V.....	0.35-0.45	0.25-0.40	1.85-2.50	.....	3.60-4.20	0.03 max.	0.04 max.	Valves
Free cutting steel.....	0.20-0.30	0.70-1.00	.....	.....	.....	0.06 max.	0.10-0.15	Houdaille brake shaft

TABLE LXVI.—AUTOMOBILE PARTS STEEL ANALYSIS. CHEVROLET MOTOR COMPANY—CHEVROLET SIX

Courtesy of the Chevrolet Motor Car Company, Detroit, Mich.

Name of Part	Carbon, Per Cent	Manga- nese, Per Cent	Phos- phorus, Per Cent	Sulphur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chromium, Per Cent	Molyb- denum, Per Cent	Vana- dium, Per Cent
Wrist pin.....	0.23-0.28	0.50-0.80	0.040	0.050	0.15-0.30	.....	0.80-1.10	.....	0.15
Exhaust valve.....	GMC 6115A.	.....	.....	.....	.....	.....	.....	.....	.....
Intake valve.....	 } Silchrome.....	.....	.....	.....	.....	.....	.....	.....	.....
Differential ring gear.....	GMC 2315A.	0.20-0.60	0.040	0.050	0.15-0.30	3.25-3.75	.....	.....	.....
Differential drive pinion.....	2315A.	0.30-0.60	0.040	0.050	0.15-0.30	3.25-3.75	.....	.....	.....
Differential side gears.....	6115A.	0.50-0.80	0.040	0.050	0.15-0.30	.....	0.80-1.10	.....	0.15
Differential pinion.....	6130A.	0.50-0.80	0.040	0.050	0.15-0.30	.....	0.80-1.10	.....	0.15
Universal joint.....	3145A.	0.43-0.48	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....
Car springs.....	6150.	0.45-0.55	0.040	0.050	0.15-0.30	.....	0.80-1.10	.....	0.15
Crankshaft.....	1045.	0.40-0.50	0.045	0.055	.....	.....	.....	.....	.....
Transmission gears (passenger car).....	6150.	0.45-0.55	0.040	0.050	0.15-0.30	.....	0.80-1.10	.....	0.15
Transmission gears (trucks).....	2515A.	0.12-0.17	0.040	0.050	0.15-0.30	4.75-5.25	.....	.....	.....
Propeller shaft.....	4140A.	0.38-0.43	0.040	0.050	0.15-0.30	.....	0.80-1.10	0.15-0.25	.....
Rear axle shafts.....	3140A.	0.38-0.43	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....
Steering knuckle.....	3135A.	0.33-0.38	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....
Steering knuckle arms.....	3130A.	0.28-0.33	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....
King pins.....	2315A.	0.13-0.18	0.040	0.050	0.15-0.30	3.25-3.75	.....	.....	.....
Connecting rods.....	1035.	0.30-0.40	0.045	0.055	.....	.....	.....	.....	.....
Pistons.....	Nickel alloy cast iron.	.....	.....	.....	.....	.....	.....	.....	.....
Cylinder block and head.....	Nickel alloy cast iron.	.....	.....	.....	.....	.....	.....	.....	.....
Connecting rod bolts.....	3135A.	0.33-0.38	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....
Universal joint bolts.....	3135A.	0.33-0.38	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....
Front and rear spring U-bolts.....	3135A.	0.33-0.38	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....
Steering arm ball.....	3135A.	0.33-0.38	0.040	0.050	0.15-0.30	1.00-1.50	0.45-0.75	.....	.....

TABLE LXVII.—AUTOMOBILE PARTS STEEL ANALYSIS. CADILLAC MOTOR CAR COMPANY—CADILLAC AND LA SALLE

Courtesy of Cadillac Motor Car Company, Detroit, Mich.

Name of Part	Carbon, Per Cent	Manganese, Per Cent	Phosphorus, Max., Per Cent	Sulphur, Max., Per Cent	Silicon, Per Cent	Nickel, Per Cent	
Transmission gears.....	0.12-0.17	0.30-0.60	0.040	0.050	0.15-0.30	4.75-5.25	Upset forging, carburized, hardened
Transmission shafts.....	0.10-0.20	0.30-0.60	0.040	0.050	0.15-0.30	3.25-3.75	Carburized, hardened
Ring gears.....	0.10-0.20	0.30-0.60	0.040	0.050	0.15-0.30	3.25-3.75	Upset forging, carburized, hardened
Rear axle pinion.....	0.12-0.17	0.30-0.60	0.040	0.050	0.15-0.30	4.75-5.25	Upset forging, carburized, hardened
Crankshaft sprocket.....	0.15-0.25	0.60-0.90	0.060	0.075-0.150	.....	.....	Carburized, hardened
Camshaft sprocket.....	.....	.....	.....	.....	.....	.....	Special hard cast iron, 25% steel scrap
Cylinder block.....	.....	.....	.....	.....	.....	1.25	Cast iron, 20% steel scrap
Pistons.....	.....	.....	.....	.....	.....	.....	0.35% molybdenum-cast iron

TABLE LXIX.—AUTOMOBILE PARTS STEEL ANALYSIS. HORCHWERKE A. G.—HORCH-EIGHT

Courtesy of Horchwerke Aktiengesellschaft Zwickau, Germany

Name of Part	Carbon, Per Cent	Manganese, Per Cent	Phosphorus, Per Cent	Sulphur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chromium, Per Cent	Molybdenum, Per Cent	Vanadium, Per Cent	Strength, 1000 Lb. per Sq. In.	Yield-point, 1000 Lb. per Sq. In.	Elongation: Gage Length		Reduction, Per Cent
												10 X Diam., Per Cent	5 X Diam., Per Cent	
Connecting rod	0.28	0.7	0.03	0.03	0.3	2.0	0.6	.....	.....	105	85	14.0	22	65.0
Crankshaft	0.36	0.75	0.01	0.01	0.3	0.5	1.0	0.4	.....	135	110	11.0	14	55.0
Vertical shaft	0.14	0.4	0.03	0.03	0.3	.....	.....	.....	.....	80	50	19.0	25	60.0
Front axle	0.24	0.6	0.02	0.02	0.3	3.5	0.6	.....	.....	120	105	11.0	17	60.0
Valve	1.4	0.27	0.02	0.02	0.4	.....	12.0	.....	.....	115	85	12.0	15	35.0
Camshaft	0.12	0.4	0.02	0.02	0.3	.....	1.0	.....	.....	125	105	12.0	16	55.0
Gear pinion	0.14	0.4	0.03	0.02	0.3	3.5	0.14	.....	.....	170	155	8.0	12	60.0
Spring	0.45	1.8	max. 0.03	max. 0.04	0.2	.....	.....	.....	.....	180	160	7.5	.....	32.8
Spring eye-bolt	0.16	0.35	0.035	0.035	0.3	.....	.....	.....	.....	85	.....	.....	.....	.....
Spring-saddle	0.28	0.6	0.03	0.03	0.3	1.5	0.5	.....	.....	100	65	14.5	.....	.....
Brake drum	0.38	0.85	0.018	0.024	0.36	.....	.....	.....	.....	93	.....	.....	.....	.....
Wrist pin	0.13	0.56	0.02	0.02	0.35	.....	0.8	.....	.....	93	60	18.0	25	60.0
Rear axle shaft	0.3	0.6	0.03	0.03	0.3	3.5	0.75	.....	.....	140	105	10.0	.....	.....
Front brake shaft	0.14	0.4	0.03	0.03	0.3	3.0	0.3	.....	.....	130	115	11.0	14	50.0

TABLE LXX.—AUTOMOBILE PARTS STEEL ANALYSIS. N. A. G.—PROTOS—PASSENGER CARS

Courtesy of Nationale Automobil-Gesellschaft, Berlin, Germany

Name of Part	Car- bon, Per Cent	Man- ganese, Per Cent	Phos- phorus, Per Cent	Sul- phur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chro- mium, Per Cent	Molyb- denum, Per Cent	Vana- dium, Per Cent	Strength, 1000 Lb. per Sq. In.	Yield- point, per Sq. In. 1000 Lb.	Elon- gation: Gage Length, 10 × Diam., Per Cent	Reduc- tion, Per Cent	Brin- ell Num- ber	DIN Num- ber
Front axle	0.32- 0.40	0.4- 0.8	max. 0.04	max. 0.04	0.35	1.5 ±0.25	0.5 ±0.20	.....	.....	105-120	100	15-12	....	70	VCN 15h
Steering knuckle arm	do.	do.	do.	do.	do.	do.	do.	.....	.....	105-120	100	do.	....	do.	do.
Connecting rod	0.3- 0.4	0.5- 0.8	do.	do.	do.	.....	.....	.....	.....	85-105	.....	20-14	....	60	St. C. 35, 61
Rear axle	0.27- 0.35	0.4- 0.8	do.	do.	do.	3.5 ±0.25	0.75 ±0.2	.....	.....	130-150	105	12-8	....	80	VCN 35h
Crank shaft	do.	do.	do.	do.	do.	do.	do.	.....	.....	130-150	105	do.	....	do.	do.
Steering spindle	0.32- 0.40	0.4- 0.8	do.	do.	do.	1.5 ±0.25	0.5 ±0.2	.....	.....	105-120	100	15-12	....	70	VCN 15h
Crown gear	0.1 0.17	max. 0.5	do.	do.	do.	3.5 ±0.25	0.75 ±0.2	.....	.....	130-170	105	12-6	....	70	ECN 35
Pinion	do.	do.	do.	do.	do.	do.	do.	.....	.....	130-170	105	do.	....	do.	ECN 35
Transmission gears	do.	do.	do.	do.	do.	do.	do.	.....	.....	130-170	105	do.	....	do.	do.

Wrist pin		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	II P
Camshaft	0.11- 0.18	max. 0.5	do.	do.	do.	do.	do.	do.	do.	do.	50	St. C 16.61
Steering lever	do.	do.	do.	do.	do.	do.	do.	do.	do.	do.	do.	do.
Crankshaft gear	0.50	0.5- 0.7	do.	do.	do.	do.	do.	do.	do.	12	do.	TG5
Valves	0.40	0.50	do.	do.	1.78	12.52	12.75	do.	do.	do.	do.	KE 965
Cylinder block	3.2- 3.5	1-1.5	do.	do.	~2	do.	do.	do.	do.	do.	180- 200	Spec Cast iron
Piston	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	do.	Nelson Bohn- alite
Springs	0.40- 0.50	0.7- 0.75	do.	do.	0.25	.....	1.0	do.	do.	do.	40	Ohr Van.
Transmission countershaft	0.1- 0.17	max. 0.5	do.	do.	0.35	3.5 ± 0.25	0.75 ± 0.2	do.	do.	do.	do.	ECN 35
Shafting for water pump	0.11- 0.18	max. 0.5	do.	do.	0.35	.....	.....	do.	do.	do.	do.	St. C. 16.61

TABLE LXXI.—AUTOMOBILE PARTS STEEL ANALYSIS. N. S. U.—PASSENGER CAR

Courtesy of NSU Vereinigte Fahrzeugwerke A. G. Neckarsulm, Germany

Name of Part	Carbon, Per Cent	Manganese, Per Cent	Phosphorus, Per Cent	Sulphur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chromium, Per Cent	Molybdenum, Per Cent	Tungsten, Per Cent	Strength, 1000 Lb. per Sq. In.	Yield-point, 1000 Lb. per Sq. In.	Elongation: Gage Length, 10 X Diam., Per Cent	Reduction, Per Cent	
Gear on camshaft	0.30	0.75	0.05	0.13	0.4	.....	.....	.....	.....	135	.....	.....	.....	Heat-treated
Differential pinion	0.15	.....	0.02	0.025	.....	2.5	1.0	.....	.....	170	150	10	55	Carburized properties refer to core
Spring bolt	0.12	0.5	0.015	0.02	0.3	.....	.....	.....	.....	85	57	18	75	
Wrist pin	0.12	0.5	0.015	0.02	0.3	.....	.....	.....	.....	85	57	18	75	
Stay tube for Cardan shaft	0.45	0.6	0.02	0.03	0.25	.....	.....	.....	.....	105	70	19	....	Normalized
Crankshaft	0.45	1.5	0.015	0.02	1.5	0.18	0.04	.....	.....	140	104	13	50	Heat treated
Connecting rod	0.35	0.8	0.02	0.03	0.3	.....	.....	.....	.....	125	106	16	65	do.
Studs, cylinder head-bolts	0.35	0.6	0.025	0.025	0.3	1.6	0.8	.....	.....	135	120	13	65	do.
Wormwheel for oil pump	0.12	0.5	0.045	0.125	0.3	.....	.....	.....	.....	90	57	18	65	Carburized properties of core
Exhaust-valve, standard model	1.5	.....	0.02	0.02	0.4	.....	13.0	.....	.....	130	85	12	40	Heat treated
Exhaust-valve, sport model	0.5	.....	0.02	0.02	.....	12.0	12.0	.....	6	130	93	24	50	Austenite
Shafting for water pump	0.5	.....	0.04	0.04	.....	.....	15.0	.....	.....	105	80	17	65	Heat treated

TABLE LXXII.—AUTOMOBILE PARTS STEEL ANALYSIS. WANDERER-WERKE
Courtesy of Wanderer-Werke, Schönau-Chemnitz, Germany

Name of Part	Car- bon, Per Cent	Man- ganese, Per Cent	Phos- phorus, Per Cent	Sul- phur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chro- mium, Per Cent	Molyb- denum, Per Cent	Copper, Per Cent	Strength, 1000 Lb. per Sq. In.	Yield- point, 1000 Lb. per Sq. In.	Elongation: Gage Length, 10 x Diam., Per Cent	Brin- nell Num- ber	Rock- well Hard- ness	Hard- ness of carbu- rized layer
Transmission gears	0.19	0.50	0.025	0.030	0.22	4.5	0.75	.....	0.05	.....	.....	.....	.....	60	
Crown gear	0.18	0.45	0.028	0.030	0.20	4.2	0.6	.....	0.04	.....	.....	.....	.....	62	
Bevel gear-pinion	0.18	0.40	0.025	0.030	0.23	4.2	0.6	.....	0.05	.....	.....	.....	.....	62	
Cylinder block	3.25	0.87	0.270	0.097	1.45	0.65	0.3	.....	0.01	.....	.....	.....	220		
Rear axle	0.28	0.50	0.030	0.032	0.20	3.6	0.55	.....	0.05	115	.....	14.0			
Connecting rod	0.30	0.58	0.025	0.030	0.28	1.5	0.3	.....	0.03	108	.....	15.0			
Front axle	0.29	0.60	0.028	0.038	0.30	1.8	0.7	.....	0.06	120	.....	13.8			
Crankshaft	0.35	0.60	0.025	0.028	0.30	4.5	0.75	.....	0.05	156	.....	11.5			
Eccentric shaft	0.35	0.70	0.028	0.030	0.25	1.5	0.1	.....	0.07	108	.....	14.2			
Camshaft	0.18	0.42	0.04	0.038	0.37	.....	0.6	.....	0.05	.....	.....	.....	.....	62	Hard- ness of carbu- rized layer
Spring bolt	0.15	0.60	0.03	0.040	0.3	.....	.....	.....	0.10	.....	.....	.....	.....	60	
Valve	1.2	0.40	0.025	0.030	4.23	.....	11.5	.....	0.05	108	.....	.....	.....		

Steering spindle	0.25- 0.40	0.40 0.80	do.	do.	do.	0.35	3.5 ± 0.25	0.75 ± 0.20	....	130-150	.....	12-8	.....	VCN35
Camshaft	0.06- 0.13	max. 0.50	do.	do.	do.	do.	do.	.....	.....	.....	.....	.....	.....	St. C.10.61
Rocking lever	0.35	0.80	do.	do.	do.	do.	do.	.....	.....	.....	.....	.....	.....	St. C.3561
Gears	0.09- 0.18	≤ 0.5	do.	do.	do.	do.	do.	~ 4.5	≥ 0.8	.....	.....	.....	.....	ECN45
Valves	1.5	0.40	do.	do.	do.	0.40	.....	13	.....	.....	.....	.....	.....	GS *
Cylinder block	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Ge2691
Piston	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Bonalite
Springs	0.30	2.0	do.	do.	do.	0.20	.....	.....	.....	190	.....	7	40	.....
Shaft for water pump	0.06- 0.13	max. 0.50	do.	do.	do.	do.	.....	.....	.....	.....	.....	.....	.....	St. C.10.61
Crankshaft	0.25 0.40	0.40 0.80	do.	do.	do.	0.35	3.5 ± 0.25	0.75 ± 0.20	.....	130-150	.....	12-8	.....	VCN35

* After information by Deutsche Edelstahlwerke, Krefeld.

TABLE LXXV.—AUTOMOBILE PARTS STEEL ANALYSIS. PEUGEOT—12CV. SIX-CYLINDER, TYPE 183

Courtesy of Soc. Anon. des Automobiles Peugeot, Paris, France

Name of Part	Car- bon, Per Cent	Man- ganese, Per Cent	Phos- phorus, Per Cent	Sul- phur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chro- mium, Per Cent	Alumi- num, Per Cent	Copper, Per Cent	Strength, 1000 Lb. per Sq. In.	Yield- point, 1000 Lb. per Sq. In.	Elongation: Gage Length, 7.2 × Diam., Per Cent	Brinell Number
Piston	.....	.....	.....	.....	.....	.....	.....	87	13	.....	.....	.....	90
Piston ring	3.00	0.5	0.70	0.07	1.5	.....	.....	.....	.....	.....	.....	.....	240
Crankshaft	0.40	0.60	0.04	0.04	0.2	.....	.....	.....	.....	136	95	14	.....
Valve	0.40	0.50	0.04	0.04	3.00	.....	10.00	.....	.....	142	.....	12	280
Front axle	0.20	0.50	0.04	0.04	0.2	2.7	0.65	.....	.....	114	95	16	250
Steering knuckle arm	0.30	0.50	0.04	0.04	0.2	2.7	0.80	.....	.....	114	95	14	250
Cylinder block	3.3	0.50	0.80	0.07	1.5	.....	.....	.....	.....	.....	.....	.....	228
Spring	0.40	0.50	0.04	0.04	1.5	.....	.....	.....	.....	185	158	10	365
Cardan shaft	0.20	0.50	0.04	0.04	0.2	2.7	0.65	.....	.....	114	95	16	250
Steering lever	0.20	0.50	0.04	0.04	0.2	2.7	0.65	.....	.....	114	95	16	250

TABLE LXXVI.—AUTOMOBILE PARTS STEEL ANALYSIS. FIAT

Courtesy of Fiat Societa Anonima, Torino, Italy

Name of Part	Car- bon, Per Cent	Man- ganese, Per Cent	Phos- phorus, Per Cent	Sul- phur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chro- mium, Per Cent	Molyb- denum, Per Cent	Vana- dium, Per Cent	Strength, 1000 Lb. per Sq. In.	Yield- point, 1000 Lb. per Sq. In.	Elon- gation, Per Cent	Reduc- tion, Per Cent	Brinnell Number
Crankshaft	0.40- 0.46	0.7	.....	.....	<0.35	.....	.....	.....	.....	114-128	93	> 12		
Intake valve	0.30- 0.32	0.55- 0.75	.....	.....	.....	5	.....	.....	.....	120	93	14	55	
Exhaust valve	0.45- 0.50	.....	.....	.....	3-4	.....	7-9	.....	.....	135-150	106-120	13-16	50-55	450-600
Eccentric shaft	0.15- 0.20	<0.5	.....	.....	<0.25	.....	.....	.....	.....	100-114	64	> 15		
Front axle	0.32- 0.38	0.70- 0.80	<0.04	0.04	<0.35	.....	0.85- 0.95	.....	.....	140-155	120-128	10-8	.....	Rockwell 31-33
Steering knuckle arm	do.	do.	do.	do.	do.	.....	do.	.....	.....	128-140	93-120	12-10	.....	Rockwell 28-31
Steering arm	do.	do.	do.	do.	do.	.....	do.	.....	.....	140-155	120-128	10-8	.....	Rockwell 31-33
Transmission gears	0.14- 0.17	.....	.....	.....	.....	2-3	0.6- 0.8	.....	.....	155-190	120-150	9-7	55-45	350-500

Propeller shaft	do.	.....	.....	.....	.....	do.	do.	do.	do.	do.	do.	do.
Differential pinion	do.	.....	.....	.....	.....	do.	do.	do.	do.	do.	do.	do.
Differential drive pinion	do.	.....	.....	.....	.....	do.	do.	do.	do.	do.	do.	do.
Differential axle shaft	0.35-0.40	.....	.....	.....	.....	do.	do.	do.	150-170	170-190	40-35	450-460
Inner brake shoe	0.14-0.17	.....	.....	.....	.....	do.	do.	do.	114-128	128-140	65-55	355-400
Steering knuckle pivot	do.	.....	.....	.....	.....	do.	do.	do.	120-150	155-190	55-45	350-500
Springs	0.35	0.7	.....	.....	1.5	.....	.....	.....	.....	190-260	.....	350-470

TABLE LXXVII.—AUTOMOBILE PARTS STEEL ANALYSIS. MORRIS MOTORS—OXFORD SIX, 1930 MODEL

Courtesy of Morris Motors, Ltd., Cowley, Oxford, Great Britain

Name of Part	Car- bon, Per Cent	Man- ganese, Per Cent	Phos- phorus, Per Cent	Sul- phur, Per Cent	Silicon, Per Cent	Nickel, Per Cent	Chro- mium, Per Cent	Molyb- denum, Per Cent	Vana- dium, Per Cent	Strength, 1000 Lb. per Sq. In.	Yield- point, 1000 Lb. per Sq. In.	Elong- ation, Per Cent	Reduc- tion, Per Cent	Izod, Ft.-Lb. Min.
Front axle beam	0.40	0.60	max. 0.06	max. 0.06	max. 0.30	0.70	.....	.....	.....	.....	.....	20	45	30
Rear axle shaft	0.30	0.55	0.04	0.04	0.30	3.5	1.0	0.55	.....	.....	.....	20	55	35
Universal joint	0.30	0.60	0.05	0.05	0.30	3.5	0.70	.....	.....	.....	.....	18	50	40
Crank shaft	0.40	0.60	0.06	0.06	0.30	1.0 max.	.....	.....	.....	.....	.....	20	40	.....
Springs	0.54	0.90	0.04	0.04	1.9	.....	.....	.....	.....	.....	.....	15	35	10
Brake drum	0.25	0.50	0.06	0.06	0.20	.....	.....	.....	.....	.....	.....	28	.....	.....
Rear axle gear	0.10	0.40	0.05	0.05	0.30	3.0	0.30 max.	.....	.....	.....	.....	18	45	40
Steering arm balls	0.10	0.40	0.05	0.05	0.30	2.0	0.30 max.	.....	.....	.....	.....	25	50	60
Cam shaft Gudgeon pin Shackle pin	0.15	0.70	0.07	0.07	0.30	.....	.....	.....	.....	.....	.....	20	50	40
Propellar shaft tube	0.32	0.55	0.04	0.04	0.30	.....	.....	.....	.....	.....	.....	.....	.....	.....
Steering arms	0.30	0.55	0.05	0.05	0.30	.....	.....	.....	.....	.....	.....	22	50	40

Case
hard-
enedBright
drawn

BIBLIOGRAPHY

Page numbers given refer to pages of this book.

	PAGE
AMERICAN SOCIETY FOR STEEL TREATING, HANDBOOK R3-R13.....	84
Transactions 1(1921), 617-638.....	121
3 (1923), 944-953.....	122
5 (1924), 315.....	144
(1924).....	86
AMERICAN SOCIETY FOR TESTING MATERIAL, 27. Convention (1924)...	145
<i>Aciers Speciaux et leurs Emplois</i> , Oct. (1925), 131-139.....	94, 96
<i>Autotechnik</i> 12 (1925), 18.....	127
20 (1925), 27.....	90
BARTON, <i>Forging, Stamping, Heat Treating</i> (1923), 102..	94, 96, 98, 101, 102, 103
Berichte d. Werkstoff-Ausschusses d. Vereins Deutscher Eisenhütten- leute, 97.....	76
BLUM, W., <i>Machinery</i> , Feb. (1929).....	147
<i>British Iron and Steel Institute</i> , Conv. May (1925).....	113
BRÜSEWITZ, F., <i>Stahl und Eisen</i> 44, (1924) 1697.....	86
CHRISTIANSEN, S. A., AND J. B. JOHNSON, <i>Stahl und Eisen</i> , 44 (1924), 1757	139
<i>Comptes rendues</i> , Delbart, 180 (1925), 934.....	61
DELBART, <i>Comptes rendues</i> , 180 (1925), 934.....	61
DEVILLE, L., AND C. HEINEN, <i>Aciers Speciaux et leurs Emplois</i> , (1925), 131- 139.....	94, 96
EDERT, <i>Stahl und Eisen</i> , 42 (1922), 962.....	134
EILÄNDER, W., AND W. ORTEL, Mitteilungen d. Fachnormen Ausschusses d. Kraft-Fahrzeug-Industrie, 10 (1926).....	163
<i>Engineering</i> , 116 (1923), 449, 483.....	64
(1919), 461.....	112
FAUST, E., <i>Stahl und Eisen</i> , 45 (1925), 1701.....	69
FELSER, <i>Stahl und Eisen</i> , 30 (1910), 2154.....	47
<i>Forging, Stamping, Heat Treating</i> (1921), 530.....	83
(1923), 102.....	94, 98, 101, 103
(1923), 408-416.....	67
FRY, AD., <i>Autotechnik</i> , 20 (1925), 27.....	90
<i>Stahl und Eisen</i> , 43 (1923), 1271.....	90
GABRIEL, E., <i>Iron Age</i> , Dec. 2 (1920), 1465-1469.....	134
<i>Genie Civil</i> , GUILLET (1922), 273, 292, 313, 337.....	82
GOERENS, <i>Stahl und Eisen</i> , 33 (1923), 438.....	60
GUILLET, <i>Genie Civil</i> (1922), 273, 292, 313, 337.....	60
GREAVES, R. H., AND I. A. JONES, <i>Engineering</i> (1919), 461.....	112
<i>British Iron and Steel Institute</i> (1925).....	113

	PAGE
HANNACK, G., <i>Stahl und Eisen</i> , 44 (1924), 1237.....	130
HEINEN, C., AND L. DEVILLE, <i>Aciers Speciaux et leurs Emplois</i> (1925), 131-139.....	94, 96
HELQUIST, T. L., <i>Machinery</i> , May (1929), 647.....	90
HULTGREN, American Society for Testing Materials, 27. conv. (1924)....	145
<i>Iron Age</i> , Dec. 2 (1920), 1465-1469.....	134
<i>Iron and Coal Trade Review</i> (1919), 373.....	112
<i>Iron and Steel Institute, Journal</i> (1905), II, 204.....	47
JOHNSON, J. B., AND S. A. CHRISTIANSEN, <i>Stahl und Eisen</i> , 44 (1924), 1757.....	139
JONES, I. A., AND R. H. GREAVES, <i>Engineering</i> (1919), 461.....	112
<i>British Iron and Steel Institute</i> (1925).....	113
<i>Journal of the Iron and Steel Institute</i> (1905), II, 204.....	47
KNOWLTON, H. B., <i>Forging, Stamping, Heat Treating</i> , Dec. (1921), 530...	83
KÖRBER, F., AND R. F. SACK, <i>Mitteilungen aus dem Kaiser Wilhelms Institut</i> , II.....	15
KUNTZE, W., AND G. SACHS, <i>Stahl und Eisen</i> , 47 (1927), 219.....	13
LEWTON, R. L., Trans. American Society for Steel Treating, 3 (1923), 944-953.....	122
LORENZ, <i>Stahl und Eisen</i> , 43 (1923), 105.....	74
<i>Machinery</i> , May (1929), 647.....	90
MAHOUX, M., <i>Revue de Metallurgie</i> , 22 (1925), 39-51.....	138
MAILÄNDER, R., <i>Stahl und Eisen</i> , 46 (1926), 1752.....	19
44 (1924), 585, 624, 657, 684, 719.....	22
MARS, G., Die Spezialstähle (Special steels), 188.....	60, 65
MAURER, E., AND R. MAILÄNDER, <i>Stahl und Eisen</i> , 45 (1925), 409.....	19
Mitteilungen d. Fachnormen-Ausschusses der Kraft-Fahrzeug-Industrie, 10 (1926).....	163
<i>Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisen-Forschung</i> , F. KÖRBER, F. SACK, II.....	15
MOSER, M., <i>Stahl und Eisen</i> , 43 (1923), 935.....	17
OBERHOFFER, P., Das Schmiedbare Eisen (Iron and Steel).....	332, 473, 482
	47, 112, 67
AND E. WEISGÄRBER, <i>Stahl und Eisen</i> , 40 (1920), 1437.....	73
ORTEL, W., AND W. EILÄNDER, Mitteilungen d. Fachnormen Ausschusses d. Kraft-Fahrzeug Industrie, 10 (1926).....	163
PARMITER, O. K., Trans. American Society for Steel Treating, 6 (1924), 315	144
PREUSS, E., G. BERNDT AND M. V. SCHWARZ, Eisenprüfung durch Ätzverfahren (Steel-testing by Etching), Berlin (1927).....	31
RAPATZ, F., Die Edelmetalle (High-grade Steels).....	77, 78, 79, 80, 92, 94, 97, 132, 134
REDENZ, H., <i>Stahl und Eisen</i> , 44 (1924), 1703.....	126
<i>Revue de Metallurgie</i> , Jan. (1925), 39-51.....	138
SACHS, G., AND W. KUNTZE, <i>Stahl und Eisen</i> , 47 (1927), 219.....	13

	PAGE
SACHS-FICK, Der Zugversuch (Tensile Strength Test).....	7
SACK, R. F., AND F. KÖRBER, <i>Mitteilungen aus dem Kaiser Wilhelms Insti- tut for Eisenf.</i> , II.....	15
SCHÄFER, R., Die Konstruktions-Stähle (Machine Steels).....	220, 70 224, 71
SCHWARZ, M. v., Metallphysik, Leipzig (1925), 5.....	31
Metall und Legierungskunde (Non-Ferrous Metals and their Alloys), Stuttgart (1929).....	100
<i>Zeitschrift d. Bayerischen Revisions Vereins</i> , 5-6 (1927).....	168
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SHEPARD, B. F., American Society for Steel Treating, Handbook, Carburiz- ing and Heat Treatment of Carburized Steels, R3-R13.....	84, 86, 89
Society of Automotive Engineers, Handbook (1929).....	386.... 10 375.... 153
<i>Stahl und Eisen</i>	30 (1910), 2154.... 47 33 (1913), 438.... 60 40 (1920), 1437.... 72 41 (1921), 1861.... 134 42 (1922), 822.... 83 42 (1922), 962.... 134 43 (1923), 105.... 74 43 (1923), 935.... 17 43 (1923), 1271.... 90 43 (1923), 1409.... 122 44 (1924), 473.... 64 44 (1924), 585.... 22 44 (1924), 624.... 22 44 (1924), 657.... 22 44 (1924), 663.... 82 44 (1924), 684.... 22 44 (1924), 719.... 22 44 (1924), 990.... 67 44 (1924), 1115.... 121 44 (1924), 1237.... 130 44 (1924), 1697.... 86 44 (1924), 1703.... 126 44 (1924), 1757.... 139 45 (1925), 409.... 19 45 (1925), 803.... 144 45 (1925), 1701.... 69 45 (1925), 1715.... 61 46 (1926), 213.... 45 46 (1926), 493.... 69 46 (1926), 1752.... 19 47 (1927), 219.... 13

	PAGE
STELBRECHT, <i>Autotechnik</i> , 12 (1925), 18.....	127
STENGER, E. P., AND B. H., Trans. American Society for Steel Treating (1921), 617-638.....	121
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6 (1924), 315. . .	144
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WEISGÄRBER, F., AND P. OBERHOFFER, <i>Stahl und Eisen</i> , 40 (1920), 1437..	72
Werkstoff. Ausschuss des Vereins Deutscher Eisenhüttenleute, Berichte, 97.....	76
WHITE, <i>Forging, Stamping, Heat Treating</i> , Sept. (1923), 408-416.	67
<i>Zeitschrift des Bayerischen Revisions Vereins</i> , 5-6 (1927).	168

INDEX

A

- Absorption of carbon, case-hardening, 75
- A.C. magnets, 128
- Acetylene welding, 58
- Acid process, electric furnace, 45
- Adjustment of valves, 135
- Advantages of cold drawing and rolling, 59
- Aggregate of ferrite and iron carbide, 35
- Airhammer used for removing of cracks, 56
- Air-hardening properties of stainless steel, 143
- Air-hardening steels, 106, 149
- Air-hardening tendency of alloy steel, 53
- Allowable working stress, 14
- Alloy boxes, 84
- Alloying elements, 40, 42
 - reduced grain size, 42
- Alloy steels, air-hardening tendency of, 53
 - diagram, 43
 - for case-hardening, 75, 80, 85
 - for gas blisters, 49
 - for heat-treating, 93, 116
 - for steel castings, 74
 - stampings, 63
 - standards for, 165
 - structure, 42
- Alloys, permeability, 128
- Alpha-iron, 34
- Altering changes of decomposition, 38
- Alternating current (A. C.) magnets, 128
- Alternating stresses, surface condition, 64
- Aluminum, coating, 146
- Aluminum connecting rods, 151
 - degasification of steel, 49
- American Society for Steel Treating, handbook, 84, 86
- American Society for Testing Materials, 71, 145
- American standards, 73, 153
- American test specimen, 10
- Ammonia, 90
- Amperage, 127
- Analysis, automobile parts, 177
 - correct, steel quality, 45
- Angle of pendulum hammer, 16
- Annealing after hot-working, 56
- Annealing, after welding, 59
 - ball-bearing steel, 124
 - before nitriding, 90
 - before testing, 65
 - boxes, 56
 - brittleness, 111
 - effect of various elements, 113
 - method of Moser, 113
 - molybdenum, 113
 - open-hearth steel, 45, 114
 - thin pieces, 115
 - case-hardening, 86
 - cold-drawn steel, 61, 63
 - object of, 56
 - process, change of structure, 57
 - recrystallization, 63
 - refining of structure, 42, 63
 - stainless steels, 143
 - steel castings, 71, 74
 - temperature, 57, 61, 115
 - air-hardening steels, 106
 - size of crystals, 63
 - steel castings, 71
 - wire, 69
 - without forming scale, 62

Antimony, 3
 Anvil of impact machine, 15
 Apparatus based on optical principle, 5
 Apparent remanence, 132
 Appearance of break, fatigue, 21
 Arsenic, 3
 Asbestos, 82
 Association of Licensed Automobile Manufacturers, 153
 Atmospheric conditions, favorable for rusting, 142
 Austenite, 31
 annealing, 58
 cold-worked metal, 63
 decomposition, alloying elements, 40, 42
 melting, 38
 tendency to decompose, 38
 Austenitic chromium-nickel steel for chemical industry, 146
 manganese steel, machinability, 63
 steels, 40
 for valves, 139
 Automatic stop on fatigue tester, 20
 Automobile parts, analysis of, 177
 Automobile steels, 1
 kinds of, 65
 manufacture of, 44
 Average breaking force, 14
 Average rupture force, 9
 Axial fissures, unequal heating, 52
 Axle, 3, 18, 65, 96, 99, 103, 149
 fatigue break, 170, 171
 straightening of, 150

B

B (symbol) DIN, 164
 Ball, Brinell tester, 22
 for ball bearings, 125
 testing hardness of, 23, 125
 Ball-bearing steels, 123, 125
 testing of, 56, 125
 Barium carbonate, 83
 Bars, checking of, 56
 heat-treated, 56
 Barton, 94, 96, 98, 101, 102, 103
 Base of ingot, torn in, 48

Basic electric furnace, 114
 open-hearth furnace, heat-treat steels, 114
 Beams, 3
 Beeswax, 82
 Bend test specimen, 10
 value, multiple bending test, 26
 Bending crankshafts, 54
 formula, use of, in testing ball bearings, 125
 forward, backward, fracture, 171
 machine for springs, 121
 test, 26
 value, Tetmay, 26
 Bent fibers in gear, 149, 172
 Bessemer, DIN, 164
 process, history, 1
 steel, 3, 44
 Bicycle bearings, 126
 Blisters, sheet metal, 68
 Blooms, testing of, 53
 Blowholes, melting of ball-bearing steel, 124
 open-hearth steel, 45
 steel without, 18
 Blum, W., 147
 Boiler plates, 18
 Bolts, 77, 80, 103
 broken, 168
 worn through, 176
 Bone charcoal, 83
 Bottom of annealing boxes, 58
 Boxes, annealing, 57
 carburizing, 84
 Brake housing, 151
 Brands of steels, new standards, 165
 Breakage, axle, 170, 171
 drop forging, 54
 Breaking, head off, from ingot, 48
 Breaking stress of material, 6
 up of cold-worked crystals, 42
 Brine, quenching stainless steel, 143
 Brinell hardness test, 22
 and scleroscope hardness, 25
 ball-bearing steel, 124
 relation to tensile strength, 24
 Brinell number, abbreviations, 23
 diameter of impression, 23, 29

Brinell test, case-hardened parts, 76
 heat-treatment, 11
 standard, 23
 Brittle material, test specimen, 12
 Brittleness, air-hardening steel, 106
 annealing, 111
 case-hardening, 86, 88
 chromium coat, 147
 martensitic steels, 40
 nitrided parts, 90
 removed by heat-treating, 91
 Broken bolts, 168
 Broken test piece, 7
 Bruesewitz, F., 86
 Brushing off scale, 56
 Burning of alloying elements, melting
 steel, 45
 of steel, heating for rolling, 53
 Burr, drop forging, 54
 ground off, 56
 Burring die, 54
 Bushings, 77

C

C (symbol) DIN, 164
 Calcium cyanamid, 87
 cyanide, 87
 Camshafts, case-hardened, 77, 80, 173
 Caps for ingot, 48
 Carbide of iron, 31, 34
 Carbon, 3, 31, 47
 alloying element, 3
 annealing brittleness, 114
 content, magnetic properties, 130
 oil-hardening steels, 107
 rust resistance, 144
 straight carbon steel, 65, 154, 164
 surface of case, 75, 86
 dioxide, 83
 monoxide, 83
 rust resistance, 143, 145
 steels standard, 154, 164
 Carbonaceous gases, 83
 Carbonates, 83
 Carburized crankshafts, 152
 gears, 148
 Carburizers, 83

Carburizing parts of the work, 82
 stainless steel, 144
 steels, soft, made in open hearth, 44
 temperature, 85
 test pieces, 85
 Case, 75
 Case-hardened parts, Brinell test, 76
 cold-working, 62
 hardness test, 76
 screws, 67
 steel, testing of, 76
 Case-hardening, fatigue effects, 77
 heating for, 85
 process, 75, 82
 salt bath, 86
 steel, 75
 Cast iron, 3, 31
 boxes, 84
 DIN, 163
 packing of piston rod, 147
 valve guides, 138
 Cast magnets, 128, 132
 steel, 70
 American standard, 73
 boxes, 84
 German standard, 72
 Cast structure of steel, destroyed by
 rolling, 52
 Casting operation, 46
 Castings, steel, walls and annealing,
 72
 Cementite, 31
 case-hardening, 86
 needles, 88
 primary, 34
 secondary, 34
 Center of crystallization, 31
 Center holes of springs, 121
 Chain pins, 77
 Changing stress, springs, 116
 Characteristic of fatigue break, 20
 of yield point, 5
 Charcoal, 83
 against soft skin, ball-bearing steel,
 124
 Charcoal keeps ingot head liquid, 48
 Charpy pendulum machine, 15
 test, chromium-silicon steel, 119

- Chassis frames, 96
- Checking bars after rolling, 56
- Chemical attack of gases, valve steel, 139
- Cherry-red heat of valves, 133
- Chilling valves in use, 136
- Chipping off, carburizing, 86, 88
 - chromium coat, 147
- Chips, annealing, 62
- Choosing material, 148
- Christiansen, S. A., 139
- Chromium, 3
 - annealing brittleness, 113
 - carbide, stainless steel, 144
 - case-hardening steels, 79, 126
 - coating, 146
 - heat-treat steels, 97
 - influence on structure, 42
 - plating, 146
 - for wear resistance, 147
 - rust resistance, 145
- Chromium-nickel air-hardening steel,
 - grinding of, 56
 - annealing brittleness, 112
 - case-hardening steel, 76, 80, 148, 172
 - heat-treat steel, 101
 - steel boxes, 84
 - steel, machinability, 63
 - soft, scale, 56
 - valves, 135, 136, 139
- Chromium-nickel-tungsten steel for valves, 142
- Chromium-silicon heat-treat steels, 100
 - steel for springs, 100, 119
 - for valves, 139
- Chromium steels, 153, 156
 - for ball-bearings, 123, 125
 - for gears, 149
 - for magnets, 130, 132
 - for nitriding, 90
 - for stainless steels, 143
 - for valves, 135
- Chromium - vanadium steel, 153, 157
 - for gears, 149
 - for springs, 123
- Classification of iron and steel, 153, 163
- Class of steel, 153, 163
- Clay, 82, 124
- Cleaning ingots, 18
 - parts for electroplating, case-hardening, 82
- Cleaning surface of springs, 123
- Clutch, 151
- Coal, 83
- Coarse grain, annealing of cold-worked material, 63
 - camshaft, 174
 - carburizing, 86
 - crystalline structure, 42
 - spring steel, 120
 - steel casting, 70
 - welding, 59
- Coarse-grained material for nuts, 69
- Coarse structure, long preheating, 53
- Coating of parts, electroplating, 82
- Coating steel with rust-resistant metals, 146
- Cobalt, 3
 - steel magnets, 132
- Cobalt-chromium steel for valves, 139
- Coercive force, 128, 130
- Coil, 127
- Coke, 83
- Cold bending properties, 26
 - brittleness, 3
- Cold drawing, 59
 - after annealing, 61
- Cold forging, air-hardening steels, 106
- Cold hardening, machinability, 63
 - effect, forging, 53
- Cold-rolled strip steel, 63, 68
- Cold-rolling, 59
- Cold-welding, 49
- Cold-worked metal, crystal structure, 42
- Cold-working, case-hardened parts, 62
 - properties of steel, 60
 - stainless steel, 144
- Colors, temper, 58, 143
- Combustion of coal, rusting, 142

- Common machinery steel DIN, 163
 - static tensile strength test, 4
 - straight carbon steel, *see* Straight carbon steel
 - Comparison of standard steel and former brands, 167
 - of valve steels, 136, 137
 - Composition of iron, rusting, 143
 - Compressed air, removing scale, 56
 - Cone, 65
 - Connecting rods, 74, 96, 103, 151
 - Constant load, 4
 - Constituents of steel, 3
 - Conversion of elongation, formula, 8
 - Cooling of burr, 54
 - iron-carbon alloys, 31
 - parts from air-hardening steel, 143
 - rapidly after welding, 59
 - stainless steel, 143
 - steel after annealing, 57
 - very slowly, large grains, 111
 - Cooling temperature after annealing steel castings, 71
 - Cooling valves, 133
 - Copper, 3
 - deposition, 82
 - sulphate, 82
 - Core, 75
 - properties, heat-treat, 92
 - toughness, 75
 - Correct annealing temperature, 57, 115
 - Corners, parts to be nitrided, 90
 - Corrosion resistance, influence of various elements, 145
 - of stainless steels, 144
 - of valves, 138
 - Cracking, chromium coat, 147
 - Cracks caused by twisting crankshaft, 56
 - chromium-silicon steel, 120
 - drop forgings, 54
 - forging stainless steel, 143
 - lengthwise, spring steel, 120
 - pressing balls, 124
 - start of fatigue breaks, 21, 67, 174
 - surface, 56
 - Cracks caused by too high quenching temperature, stainless steels, 143
 - Crankshafts, 3, 18, 99, 100, 101, 103, 151
 - ball bearings, 126
 - carburized, 152
 - fatigue break, 169
 - made in parts, 126
 - manufacture of, 54
 - speed, 152
 - throw cut out of the solid, 55
 - Craters formed in welding, 58
 - Cross fissures from rapid heating, 52
 - Cross grinding of springs, 123
 - Cross-head of test piece, 15
 - Cross-sectional area, original, 4
 - Crown gears, 149
 - Crucible, 1
 - Crumbling chip, pressed nuts, 69
 - high-carbon chromium steel, 135
 - Crust of salt, 88
 - Current, electric, 127
 - reversing, magnetism, 128
 - Curve, magnetic, 127
 - Cutters, 3
 - Cutting, disk from bar, testing, 56
 - glass, 90
 - of steel with phosphorus, 63
 - of steel with silicon, 64
 - properties of ball-bearing steel, 124
 - speed, 56, 149
- D
- Dark red heat, valves, 133
 - D. C. magnets, 128
 - Decarburization, 88
 - annealing, 57
 - excessive, 114
 - fatigue, 122
 - Decomposition of austenite, alloying elements, 42
 - fast cooling, 38
 - slow cooling, 34
 - Decreasing load, 4
 - Deep drawing sheet metal, 68
 - Deflection permanent, springs, 116

Deformation, 3
 break, 168
 cold-working, size of crystals, 63
 valve head, 135
 Deformed volume, 17
 Degasification, 45
 open-hearth furnace, 45
 Delbart, 61
 Demagnetization, 129
 Deoxidation, 45
 case-hardening steel, 88
 welding, 58
 Dependability of welds, 59
 Depth, carburizing, 75, 85, 87
 case-hardening camshaft, 173
 hardening alloy steels, 75
 impression, Erichsen test, 27, 28
 soft skin, 126
 Designating steel, DIN, 164
 Deville, L., 94, 96
 Deutsche Industrie Normen, 163
 Diagram, alloyed steels, 43
 field induction, 127
 Diameter, magnet, 133
 Dies, drop forging, 54
 plated with chromium, 147
 removing burr, 54
 Diesel engine, 147
 Differential gears, 149
 Differential housing, 151
 DIN, numbering system, 163
 standards, 26, 67, 163
 Dipping parts, electroplating, 82
 case-hardening, 86
 Direct-current magnets, 128
 Disadvantage of case-hardening, 88
 of cold drawing and rolling, 59
 Discard on ingot, 48
 Disk cut off from bar, testing, 56, 126
 Double hardening treatment, 86
 Drawing parts, 111
 properties of sheet metal, testing,
 27
 springs after hardening, 121
 stainless steel, 144
 steps, wire, 69
 temperature, fatigue, springs, 121
 Drilling ingots for analysis, 50

Drills, 3
 Dripping, ingot, 53
 Drop forgings, 54
 fiber of steel, 54
 Drop hammer, 54
 Dry grinding, springs, 123
 Ductility, stainless steel, 145
 test, 27
 Dull fracture, 124
 Durability of boxes, 84
 Dust, 84
 Dynamic forces, tensile test, 14

E

E (symbol) DIN, 164
 Eccentric rolls, springs, 121
 Eccentrically stressed valve, 135
 Economic limit, machinability, 109
 Eddy current, 129
 Efficiency of engine, temperature,
 133
 Eight-cylinder engine, crankshaft, 56
 Eiländer, W, 163
 Elastic deformation, 4
 Elastic limit, 4
 of valve steel, 135
 Electric arc welding, 58
 basic process, 45
 butt welding, valves, 142
 energy, loss of, 128
 field, 127
 furnace, 44
 heating test specimen, 135
 process, 1
 steel, 3
 Electric properties, 127
 Electrical requirements, 128
 resistance, 129
 Electrochemical nature of rust proc-
 ess, 142
 Electroplating parts, case-hardening,
 82
 Elements of magnetism, 127
 Elongation, 4, 6
 correct values, 7
 ever-oxidized steel, 45
 per unit of original length, 6

End of test pieces, influence on test, 8, 12
 End temperature, rolling forging, 53
 End temperature, forging of ball-bearing steel, 124
 Ends break out, ball-bearing steel, 124
 Energy, electric, loss of, 128
 Equilibrium condition, iron-carbon diagram, 38
 Erichsen test, deep-drawing sheet metal, 27, 68
 Etching, troostite, 38
 Eutectic, iron-carbon alloy, 32
 Eutectoid, iron and cementite, 34
 Evolution of gases, 84
 Excessive decarburization, 114
 Excess material, drop forging, 54
 Exhaust pipes, 67
 Exhaust valves, 133
 Exhaustion, carburizers, 84
 Eyelets for springs, 116, 121

F

Failures, 88, 168
 stainless steels, 145
 Fast cooling, fissures, 52
 Fatigue, decarburizing, 122
 drawing temperature, springs, 122
 effect on case-hardened parts, 77
 fractures, 21, 67, 169, 170, 171
 relation to hardness, springs, 122
 resistance of finished parts, 64
 strength, hardening temperature, 122
 test, 19
 piece, 21, 77
 relation to yield point, 22
 values, comparison of, 22
 Fatigue breaks, appearance, 20
 axle, 170, 171
 crankshaft, 169
 springs, 174, 175
 start of, 20, 123, 174
 steering spindle, 170
 Faults, drop forging, 54
 Faulty form of die, 54
 Faust, E., 69
 Felser, 47
 Ferrite, 34
 heat-treat, 110
 Ferro-chromium, melting steels, 44
 Ferro-manganese melting steel, 44
 electric furnace process, 44
 Ferro magnetic body, 127
 Ferro-vanadium, 100
 Fibers, gears, 149, 172
 of steel, strength, 50
 short, chromium case-hardening steels, 79
 Fibrous structure, rapidly cooled pieces, 115
 springs, 79
 Field, 127
 intensity, 127
 File test, 75
 Filed parts, fatigue resistance, 64
 Fillet for corners, 168
 test specimen, 11, 12
 Final cold drawing, 62
 Final grinding eliminated by nitriding, 90
 Fine grain, twice quenching, 86, 94
 Fine structure, carburized parts, 86
 from hardening, 91
 pressing nuts, 69
 steel castings, 72
 Finish, resistance to fatigue, 64
 grinding, case-hardening, 85, 88
 rolling grains size, springs, 120
 Firebrick caps for ingots, 48
 welding, 58
 Fissures, axial, high-alloy ingots, 52
 unequal heating, 52
 cold welding, 49
 cross, 52
 fast cooling, 52
 forging open-hearth steel, 45
 preheating, 52
 too rapid heating, 52
 Flaking, chromium coat, 147
 Flat shrinkage cavity, 48
 Flat test specimen, 12, 13
 conversion of section, 13, 14
 gage width of, 12
 Flats, rolled steel, fracture, 171

Flats, springs, 116
 Flattening test, 26
 Flaws, slags, 46
 Flux, welding, 58
 Flywheel, 151
 Folding properties, sheet metal, 27
 Folds, drop forging, 54
 Forgability stainless steel, 143
 high-alloy nickel steel, 91
 Forged boxes, 84
 Forged crankshaft, 54
 Forging air-hardening steel, 106
 carbon-chromium steel for ball
 bearings, 124
 for valves, 135
 magnet steels, 130
 open-hearth steel, fissures, 45
 or rolling, 52
 refining structure, 42
 steel, 52
 temperature, 53
 soft steel, 53
 test, 26
 Forgings, cleaning, 64
 gears, 149
 preheating of, 109
 scale, 109
 Formation, shrinkage cavity, 48
 Forms, ingot, 51
 Forms of carbon in iron, 31
 Foundation impact machine, error,
 15
 Four-cylinder engines, crankshaft, 56
 Fracture, ball-bearing steel, 124
 case-hardened parts, 86
 granular, annealing brittleness, 112
 smooth velvety, alloying elements,
 42
 Free carbon, 35
 Free cementite, ball-bearing steel, 124,
 126
 Free ferrite, 36
 heat-treat, 110
 Freezing, in ladle, 46
 of stem in guides, 138
 Front axle, 150
 Fry Ad., 90
 Furnace for cooling forged steel, 53

G

Gage, length, 5, 7
 marks, 6
 torsion test, 27
 width, test specimen, 12
 Gas, against soft skin, 124
 blisters, alloy steels, 49
 bubbles, trapped in steel, 49
 carburization, 83, 86
 inclusions, steel without silicon, 49
 productivity, carburizer, 83
 segregations, 49
 Ge (symbol), DIN, 163
 Gears, cast-steel, 74
 chromium plated, 147
 cut from forged or rolled bar, 172,
 176
 forged, 172, 176
 noise, 147
 steel for, 3, 77, 80, 148
 straight and bent fibers, 172
 German industrial standards, 72, 163
 chromium heat-treat steels, 99
 standard test pieces, impact test, 18
 standard test specimen, 12
 Glass, 83
 cutting with nitrided steel, 90
 hardness, 75
 Goerens, 60
 Goltze, hysteresis graphs, 129
 Grains, growth, heating, 41
 reduced by alloying elements, 42
 solidified iron, 31
 springs, 120
 Granular fracture, annealing brittle-
 ness, 112
 interior of fatigue break, 20
 Granular pearlite, 40
 Graphite, 31
 Gray cast iron, 31
 Greatest elongation, 6
 Greatest reduction of area, 8
 Greaves, R. H., 112, 113
 Grinding, carburized parts, 85, 88
 marks on springs, 123, 174
 off burrs, 56
 rustproofing, 144
 springs, 123

K

- Keyway start of fatigue break, 170
- Knowlton, H. B., 83
- Körber, F., 15
- Krupp, fatigue testing machine, 19
 - nitriding, 90
 - stainless steel, 142
- Kuntze, W., 13

L

- Lamellar ball-bearing steel, 124
 - pearlite, 35
- Large ingots, preheating of, 52
- Large sections through hardening, 91, 94, 101
- Lathe tools, 3
- Laws of similarity, 19
- Layers of solidification, 47
- Lead bath, patenting, 69
- Lead coating, 146
- Leather charcoal, 83
- Leaves, springs, 116, 121
- Ledeburite, 32
 - alloyed steels, 42
- Length, magnet, 133
- Lengthening of test piece, 135
- Lengthwise grinding of springs, 123
- Level road, valves, 133
- Levers, 65, 77, 96, 103, 151
- Lewton, R. H., 122
- Light cars, springs, 118
- Line of stress, testing, 12
- Liquid metal poured on ingot head, 48
- Load, Brinell tests, 23
 - testing, 4
- Location of the rupture, 7
- Lorenz, 74
- Lost head, ingot, 48, 51
- Low annealing grain size, springs, 120
- Low-carbon, case-hardening steel, 104
 - content, fatigue, 122
- Low-carbon heat-treat steels, 104
 - nickel steel, scale, 110
 - oil-hardening steel, 107
 - self-hardening steel, 42
- Low end-temperature, fissures, 53
- Low-priced cars, springs, 116

- Lower transformation point, annealing, 57
- Lower yield point, 5
- Luting of boxes for annealing, 62, 124
 - for carburizing, 85

M

- M (symbol) DIN, 164
- Machinability, 63
 - limit of, 63, 109
- Machine steel, 3
 - to form eyelets, 121
- Machined crankshaft, 55
 - test pieces, 5
- Machining heat-treated parts, 76, 109
- Magnetic curve, 128
- Magnetic induction, 127
- Magnetic iron, 35
- Magnetic properties, 127
 - resistance, 129
- Magnetism, 127
- Magnetization curve, 127
- Magnetizing cobalt steels, 132
 - force, 132
- Magnets, short, 133
 - steel, 127
- Mahoux, M, 138
- Mailander, R., 19, 22
- Main leaf, springs, 116, 121
- Malleable iron, DIN, 163
- Mandrel, bending test, 26
 - test, 26
- Manganese, 3, 47
 - annealing brittleness, 92, 113
 - austenitic steels, 40
 - brittleness, 88
 - case-hardening steels, 44, 88
 - content, American nickel steels, 95
 - influence on structure, 42
 - rust resistance, 145
 - silicon spring steel, 117
 - spring steels, 117
 - steel, machinability, 63
- Manometer, testing machine, 13
- Manufacture of automobile steels, 44
 - of springs, 120
 - of stainless steels, 143

- High end temperature, change in dimensions, 53
 High-grade steels, standards, 166
 High-priced cars, springs, 116, 117
 High-speed engines, 127, 133
 High-speed steel, 42
 for valves, 135
 High temperature, properties at, 133
 influence on rusting, 142
 History of standardization in United States, 153
 in Germany, 163
 Holes for bolts, springs, 121
 Homogeneous solid solution of austenite, 31
 Homogenizing ingot, ball-bearing steel, 124
 Hot brittleness, 3
 Hot-rolled bars, scale, 56, 110
 Hot-rolling strips, 63
 Hot-shortness, manganese, 145
 Hot strength, 135
 Hultgren, 145
 Hydrogen, chromium coating, 146
 gas welding, 58
 Hysteresis, 128
 loss, 129
- I
- Identical condition for testing hot strength, 135
 Immunity of cobalt magnets against vibrations, 133
 Impact machine, 15
 Impact stress, valves, 134
 Impact test, 15
 detects wrong heat treatment, 19
 German standard test piece, 18
 importance of, 19
 pieces, relation temperature, toughness, volume, 19
 working constant and reduction of area, 19
 Impact toughness, 8, 16
 Impression, Brinell test, 23
 Improving influence of vanadium, 100, 108
- Impurities, ingot, 46, 48
 Induction, magnetic, 127
 Industrial centers, rusting, 142
 Influence of fiber of steel on strength, 50
 Influence of temperature, forging rolling, 53
 Ingot, base of, 48
 breaking head of, checking, 53
 dripping, 53
 fire-brick caps, 48
 form of, 48, 51
 head kept liquid, 48
 high-alloy steels, 51
 lost head, 48
 molds, 51
 notching after rolling, 53
 section, 52
 size, ball-bearing steel, 124
 size of grain, 69
 small, 51
 solidification, 47
 weight, 52
 Inspecting material, 26, 163
 Insulating sheet metals, magnets, 129
 Intake valves, 133
 Intensity of field, 127
 Intermediate annealing, case-hardening, 86
 Internal strains, from cooling, 52, 56
 from hardening, 89
 Introduction, 1
 Iron, melting point, 31
 oxide, 142
 in molds, 52
 Iron carbide, 34
 Iron-carbon alloys, 31
 diagram, 36
 Irregularly shaped forgings, testing, 10
- J
- Jigs for hardening, 89, 111
 Johnson, J. B., 139
 Jones, I. A., 113

K

- Keyway start of fatigue break, 170
- Knowlton, H. B., 83
- Körber, F., 15
- Krupp, fatigue testing machine, 19
 - nitriding, 90
 - stainless steel, 142
- Kuntze, W., 13

L

- Lamellar ball-bearing steel, 124
 - pearlite, 35
- Large ingots, preheating of, 52
- Large sections through hardening, 91, 94, 101
- Lathe tools, 3
- Laws of similarity, 19
- Layers of solidification, 47
- Lead bath, patenting, 69
- Lead coating, 146
- Leather charcoal, 83
- Leaves, springs, 116, 121
- Ledeburite, 32
 - alloyed steels, 42
- Length, magnet, 133
- Lengthening of test piece, 135
- Lengthwise grinding of springs, 123
- Level road, valves, 133
- Levers, 65, 77, 96, 103, 151
- Lewton, R. H., 122
- Light cars, springs, 118
- Line of stress, testing, 12
- Liquid metal poured on ingot head, 48
- Load, Brinell tests, 23
 - testing, 4
- Location of the rupture, 7
- Lorenz, 74
- Lost head, ingot, 48, 51
- Low annealing grain size, springs, 120
- Low-carbon, case-hardening steel, 104
 - content, fatigue, 122
- Low-carbon heat-treat steels, 104
 - nickel steel, scale, 110
 - oil-hardening steel, 107
 - self-hardening steel, 42
- Low end-temperature, fissures, 53
- Low-priced cars, springs, 116

- Lower transformation point, annealing, 57
- Lower yield point, 5
- Luting of boxes for annealing, 62, 124
 - for carburizing, 85

M

- M (symbol) DIN, 164
- Machinability, 63
 - limit of, 63, 109
- Machine steel, 3
 - to form eyelets, 121
- Machined crankshaft, 55
 - test pieces, 5
- Machining heat-treated parts, 76, 109
- Magnetic curve, 128
- Magnetic induction, 127
- Magnetic iron, 35
- Magnetic properties, 127
 - resistance, 129
- Magnetism, 127
- Magnetization curve, 127
- Magnetizing cobalt steels, 132
 - force, 132
- Magnets, short, 133
 - steel, 127
- Mahoux, M, 138
- Mailander, R., 19, 22
- Main leaf, springs, 116, 121
- Malleable iron, DIN, 163
- Mandrel, bending test, 26
 - test, 26
- Manganese, 3, 47
 - annealing brittleness, 92, 113
 - austenitic steels, 40
 - brittleness, 88
 - case-hardening steels, 44, 88
 - content, American nickel steels, 95
 - influence on structure, 42
 - rust resistance, 145
 - silicon spring steel, 117
 - spring steels, 117
 - steel, machinability, 63
- Manometer, testing machine, 13
- Manufacture of automobile steels, 44
 - of springs, 120
 - of stainless steels, 143

- Marked test pieces, 6
 Marking machine, 6
 Marks from grinding causes break of spring, 174
 Mars, G., 60, 65
 Martens, hardness test, 25
 Martensite, 38, 40
 Martensitic steels, 40
 case-hardening steels, 78
 Material, railroad vehicles, DIN, 163
 Maurer, E., 19
 Maximum load, 6
 Measuring, annealing temperature, 57
 elastic limit, 5
 elongation, 5
 proportional limit, 5
 Melting apparatus, treatment of steel in, 44
 Melting of austenite, 38
 of ball-bearing steel, 124
 of stainless steels, 145
 Melting point of iron, 31
 Melting process, 44
 Metal boxes, annealing, 57
 Metallography, 31
 Middle third, test piece, 7
 Mild quench, 110
 Milling ingots, analysis, 50
 Miscellaneous steel, DIN, 163
 Mistakes, case-hardening, 88
 hardening ball-bearing steel, 126
 spring steel, 120
 Molds, ingots, 51
 Molybdenum, 3
 reduces annealing brittleness, 109, 113
 steels, 108, 153, 155
 gears, 149
 Monel metal, valves, 140
 Moser, test of, 17
 Multiple bending test, 26
- N
- National Automobile Chamber of Commerce, 153
 Nature of heat treatment, 91
 Needle structure of martensite, 38
 Needles of iron carbide, 34
 Neukurve, 127
 Neutral axis, fatigue test piece, 20
 Nickel, 3
 annealing brittleness, 113
 austenitic steels, 40
 Nickel carbon steel, 153, 155
 case-hardening steels, 77
 Nickel-chromium steel, 153, 156
 heat-treat steels, 93
 influence of, 102
 influence on structure, 42
 Nickel plated sheet metal, 68
 Nickel plating, 146
 Nickel steel, case-hardening without warping, 90
 stainless steel, 143
 open-hearth furnace, 44
 Nitriding, 90
 process, disadvantages, 90
 Nitrogen, 86
 Noise of gears, 147
 Non-magnetic austenite, 35
 Non-magnetic nickel steel for valves, 135
 Normalized steel, 58
 Notch tests, bending, 15
 breaking, 16
 strike, 15
 test, chromium-nickel case-hardening steel, 77, 80
 tensile strength, relation to, 19
 Notch toughness, 16
 chromium-silicon steels, 101
 high-end temperature, rolling, 53
 over-oxidized steel, 45
 valve steel, 139
 Notching bloom after cooling, 53
 Notching test pieces, forging test, 26
 Number, Brinell, 23
 Number of strokes, required for breakage, 122
 Number of turns, 127
 Number system, classification of steel, 153, 163
 Nuts, pressed, 63, 69

O

Oberhoffer, P., 47, 67, 72, 112
 Octagonal section of ingot, 52
 Oertel, W., 163
 Oil-hardening alloy steel castings, 74
 steels, 107
 Oil paint coatings, 146
 Oil pump, Brinell tester, 22
 Olsen machine, 121
 Open-hearth furnace, 44
 history, 1
 screw steel, 67
 steel, 3
 Ordering steel DIN, 164
 Original area, 4
 Outer zone of ingot 47, 50
 Over-forged steel castings, 74
 Overheating, carburizing, 88
 Overheating stainless steel, polishing,
 144
 Overlaps in drop forging, 54
 Overoxidized steel, elongation and
 toughness, 45
 Oversize parts, case-hardening, 83
 Oxidation, resistance of stainless
 steels, 143
 Oxides, case-hardening steels, 88
 Oxidizing atmosphere, 88
 Oxidizing valves, 134, 138
 Oxygen content in stainless steel, 145

P

Packing parts, case-hardening, 75, 76,
 84
 Paint, 146
 Parmiter, O. K., 144
 Pasting, case-hardening parts, 82
 Patenting process, wire, 69
 Pearlite, 34
 spheroidal, annealing, 57
 Pedals, 151
 Pendulum, impact tester, 15
 testing machine, 15
 Penetrator, Rockwell tester, 76
 Percentage elongation, 6
 Permanent deformation, 4
 Permanent magnets, 129

Permeability, 127
 Phosphorus, annealing brittleness,
 113
 cold-working properties, 3
 hot-working properties, 69
 machinability, 63
 segregation 47
 stainless steel, 145
 Pickling, fatigue breaks, 64
 sheet metal blisters, 68
 strips, 63
 wire, 63
 Pig iron, 3, 32
 Pipes, carburizing, 84
 DIN, 163
 form and location of, 47
 form of ingot, 48, 51
 testing for, 53
 Piston, pins, 151
 Piston rod, 147
 Pits of corrosion, valves, 138
 Plain carbon steel, *see* Straight carbon
 steel
 Plain static stress, 14
 Planimeter, 9
 Planing hard workable steel, 63
 Planing ingots, analysis, 50
 Plastic deformation, 4
 Point of rupture, 5
 Pointing flats, springs, 121
 Poisonous baths, 87
 Polished parts, fatigue resistance, 64
 Polishing, rustproofing, 144
 Poor working qualities, 45
 Poorly melted steel, 45
 Porous spots, ingot, 52
 Potash, 82
 Potassium chloride, 86
 Potassium cyanide, 83, 86
 Pouring from above, pipes, 46, 48
 from below, pipes, 46, 48
 of ball-bearing steel, 124
 overoxidized steel, 44
 silicon steels, 49
 steel, 45, 46
 made in electric furnace, 45
 in open-hearth furnace, 45
 temperature, ingot, 46, 48

Practical tests, 26
 Predominant alloying elements, 153
 Preforming drop forgings, 54
 Preheating forgings for heat-treat, 109
 Preheating furnace, 52
 Preheating ingots before rolling, 52
 Preparation of parts for case-hardening, 82
 Pressed nuts, 63, 69
 Pressed parts, 67, 69
 Pressing magnets, 130
 Pressing properties of sheet metal, testing of, 27
 Pressing stainless steels, 144
 Pressure, Brinell tester, 23
 per square inch of nitrided parts, 90
 Preventing changes of decomposition, 40
 Price of tungsten steel, 132
 Primary cementite, 34
 Primary part of transformer, 129
 Probable elongation, 7
 Products of decomposition, of austenite, fast cooling, 38
 slow cooling, 34
 Properties of steel, at high temperature, 133
 cold-drawn steel, 60
 after annealing, 62
 electric, magnetic, 129
 end temperature of rolling, relation to, 53
 of core, 76
 rate of cooling, relation to, 111
 relation to structure, 42
 steel castings, 73
 Proportional limit, 4
 Proportional test specimen, 11, 13
 Protection of steel, 142
 Protective effect of copper coating, 82
 Punching center holes on springs, 116
 Punching holes for eyelets, 121
 Purchaser's inspection, 26
 Pure iron, for magnets, 128
 melting point, 31
 Purifying qualities of vanadium, 108
 Pyrometer for manufacture of springs, 121

Q

Quality figure, 130
 Quenching in oil, case-hardening, 86
 case-hardening parts, 75, 86
 steel, 75
 spring steel, 116
 stainless steel, 143
 steels, 110
 valves, high-carbon chromium steel, 136

R

Races, ball bearings, 125
 Racing cars, valves for, 142
 Railroad material, 163
 Railroad track material DIN, 163
 Rapatz, F., 77, 78, 79, 80, 92, 94, 97, 98, 132
 Rapid carburizing, 83
 Rapid cooling, annealing, brittleness 112
 after welding, 59
 austenite, 38
 steel castings, 72
 Rate of cooling, 38
 properties, 58, 112
 Ratio of induction to field intensity, 127
 of length to diameter of magnet, 133
 of strength and deformation, 9
 Re-annealing, 115
 Rear axle housing, 150
 steel for, 150
 Receptacles for annealing, 62
 Recording device for torsional test, 27
 Recrystallization, 42
 of cold-worked metal, 63
 Redenz, H., 126
 Reduction of area, 5, 6, 8, 13
 in ball-bearing steel, 124
 Reduction of section, rolling, 52
 Refined steel, 1
 Refining grains size, case-hardening, 86
 steel castings, 70
 Refining process, 44
 Regenerating of carburizers, 83
 Rehardening after annealing, 62

- Rejections, hardening magnets, 130
 - Remagnetizing, 129
 - Remanence, 129
 - true and apparent, 132
 - Remedies for mistakes, case-hardening, 89
 - Removing burr from drop forging, 54
 - Removing parts of carburized layer, 83
 - Removing scale for hardening, 110
 - Replacing cobalt by chromium, 132
 - Requirements for valves, 134
 - Residual magnetism, 128, 129
 - Resistance, against corrosion, 134, 145
 - against demagnetization, 129
 - against impact stress, 134
 - electrical, 129
 - increased through fillets, 168
 - magnetic, 128
 - to acids, 145
 - to air, 146
 - to heat, stainless steel, 136
 - to salt water, 146
 - to scaling, 139
 - Resting of steel before pouring, 46
 - Retention of austenite, hardening stainless steel, 143
 - Reversing current, magnetism, 128
 - Rings for ball bearings, 125
 - for testing of bars, 125
 - Rings made in two parts, 127
 - Rivets, 67
 - Rockwell tester, case-hardened parts, 76
 - Rolled test pieces, 5
 - Roller bearings, 79
 - Rollers, 77, 79
 - Rolling, end temperature, 53
 - eyelets, springs, 121
 - Rolling in of scale, 56
 - Rolling magnet steels, 130
 - spring steel, 120
 - steel, 52
 - sulphur causes breaks, 64
 - Rolling or forging, 52
 - Room temperature, structure of iron-carbon alloy, 37
 - Rosin, 82
 - Rotating field magnets, 133
 - Round test specimen, 11, 13
 - Rounding ends, spring leaves, 121
 - Rubbing spring leaves with wood, 121
 - Running in, gears, 149
 - Running qualities, nickel steels, 96
 - Rupture, carburized parts, 88
 - diagram, 4
 - force, average, 9
 - point, 5
 - reports, 5
 - test piece, 13
 - work, 9, 15
 - specific, 9, 15
 - Rust, carburizing, 82
 - Rusting, 142
 - Rustless iron, 142
 - Rustproofing, 146
 - Rust-resistant steel, 142
- S
- Sachs, G., 13
 - Sachs-Fick, 7
 - Sack, R. H., 15
 - SAE handbook, 10, 153
 - Sagging of parts, 109
 - Salt, 83
 - bath, 86
 - Sand, 83
 - blasting, forgings, 64
 - springs, 123
 - Sawdust, 82
 - Scale, breaking off, 5, 56
 - forgings, 109
 - hot-rolled bars, 110
 - of diagram, 9
 - testing machine, 5
 - Scaling of valves, 139
 - Schäfer, R., 70, 71
 - Schematic view, shrinkage cavities, 47
 - Schwarz, M. v., 31, 100, 168
 - Scientific research, steel for, 58
 - Scleroscope, 25
 - case-hardened parts, 76
 - hardness and Brinell hardness, 25
 - Scrap, acid electric furnace, 45
 - Scraping off scale, 56
 - Scratch method, Martens, 25

- Scratch on spring, break, 123, 174
- Screw machine steel, 59
with silicon, cutting qualities, 64
- Screw steel, 65, 154
- Seamless pipes, ball-bearing steel, 125
- Seat of valves, 133
- Secondary cementite, 34
- Secondary part of transformer, 129
- Section of part, hardening temperature, 110
- Section of test piece, core, case-hardening, 76
- Segregated chromium and chromium carbide, open-hearth steels, 45
- Segregation, 45, 47
corrosion, 145
maximum enrichment, 47
order of, 47
persisting throughout working, 49
testing, 49
- Selection of steels, 148
- Self-aligning balls for test specimen, 10
- Self-hardening steel, 42
case-hardening, 90
- Sensitiveness, chromium-silicon steel, 119
high-carbon chromium steel valves, 135
- Shaftings, 65, 77, 96, 151
- Sharp corner of keyway starts fatigue break, 170
- Sharp corners, stresses in, 168
- Sheet metal, 67
Bessemer process, 44
deep drawing, 68
DIN, 163
nickel plated, 68, 146
testing of, 26, 27
tinned, 68
- Shell for testing case-hardening steel, 77
- Shephard, B. F., 84, 86, 89
- Shore scleroscope, 25
case-hardened parts, 76
- Short fiber, chromium case-hardening steel, 79
magnets, 133
- Shrinkage, carburizers, 84
- Shrinkage cavities, 47, 48
- Shutting engine, chilling valves, 136
- Silchrome steel, valves, 138
- Silicon, 3, 47
annealing brittleness, 113
cutting quality, 64
case-hardening steels, 88
degasifies steel, 49
manganese steel, 153, 157
rust resistance, 145
spring steel, 100, 119
steel, 69
crystal skin, 49
magnets, 129
- Six-cylinder engine, crankshaft, 56
- Size of crystals, recrystallization, 63
grains, pressed nuts, 69
spring, 120
ingot, ball-bearing steel, 124
magnets, 133
- Skin of crystals, pouring ingot, 49
- Skin, thickness of oxide, 143
- Slag, case-hardening steel, 88
removing of, 45
rust resistance, 144
- Slow cooling, annealing brittleness, 111
nickel steel, 90
nitriding, 90
- Slow heating, stainless steel, 143
- Slowly combustible carburizer, 85
- Small boxes, 85
- Small ingots, 51
- Small parts, stainless steel, 143
- Small radius, start of fatigue break, 169
- Smearing in bearings, 101
- Society of Automotive Engineers, 153
- Soda, 87
lye solution, 82
- Sodium, 86
chloride, 87
cyanide, 87
- Soft chromium steels, 99
- Soft chromium nickel steel, scale, 56
- Soft material, test pieces, 12
close to size, 62

- Soft pure iron, magnets, 128
Soft skin, ball-bearing steel, 124, 126
Soft spots, 79, 82, 84, 88, 89, 109, 126
 stainless steel, 143, 144
Soft steel, 4, 7
 balls, 124
 DIN, 163
 forging temperature, 53
 machinability, 63
 screws, 67
 sheet metal and rivets, 67
 stainless steel, 143
 wire, 69
Soft, tough steels, machinability, 63
Soiled fracture, 124
Solid solution, 31
Solidification of iron, 31
 in mold, 46
Solubility of carbon in iron, 34
 in austenite, alloying elements, 42
Solution of chromium carbide, stainless steel, 144
 of ferro chromium, ball-bearing steel, 124
Sorbite, 38, 41
 fine structure of, 38, 41
Sorbitic state of forged chromium steel, 124
Sorbitic steels, notch toughness, 124
Sparking, wood, 121
Sparkling grains, 88, 126
Special steel, DIN, 163
Specific gravity, valve steel, 134, 139
Specific impact work, 16
Specific rupture work, 15
Specific weight, 134
 carburizer, 84
Specimen, *see* Test specimen
Speed of crankshaft, 152
 of deformability, 18
 stress of valves, 133
Speedometer gears, 147
Spherical bearing for test pieces, 10, 15
Spheroidal form of pearlite, 57, 124
Spindles, 65
Spoiling hardness, grinding, 88
Springs, break caused by scratches, 174
 manganese steel, 117
 manufacture of, 121
 pins, 77
 rupture, 175
 steels, 100, 116
 best, 117
 fatigue, 121
 rolling of, 116, 120
 test, 121
Sprockets, 77, 80
Square section of ingot, 52
St¹(symbol), DIN, 163
Stainless steels, 142
 annealing, 143
 forging, 143
 temper colors, 143
 valves, 136, 139
Stampings, 63, 65
 alloy steel, 63
Standard alloyed steels, 165
Standard Brinell test, 23
Standard gage length, 7
Standard testing material, 163
Standardization of steel, 153
Start of fatigue break, 20
Static stress, plain, 14
Static tensile strength test, 4
Stationary parts, carrying current, 133
Steam for removing scale, 56
Steel, analysis of automobile parts, 177
Steel castings, 70
 American standards, 73, 155
 DIN, 72, 163
 forged, 74
 pressed into dies, 74
 test pieces, 72
Steep grade, heating of valves, 133
Steering spindles, 96, 150
 fatigue break, 169
Stelbrecht, 127
Stem of valve, lengthening, 135
 stainless steel, 136
Stenger, E. P. and B. H., 121
Stg. (symbol), DIN, 163

- Sticking in guides, 136
- Stock of steel, 165
- Straight bars, 59
- Straight carbon carburizing steel, 77, 86
 - DIN, 165
- Straight-carbon heat-treat steel DIN 91, 165
- Straight carbon steels, annealing
 - brittleness, 92
 - analysis, 65
 - axles, 149
 - cold-worked, recrystallization temperature, 63
 - DIN 1611 B, 164
 - heat-treating of, 91
 - levers, 151
 - quenching, 110
 - scale, 56
 - springs, 116
 - standard, 153, 154
 - welding, 58
- Straight fibers, gears, 149, 172
- Straight nickel carburizing steel, 77
- Straightening, after annealing, 115
 - axles, 150
 - carburized parts, 87, 89
 - heat-treated parts, 109
 - spring leaves after hardening, 121
- Strain between burr and forging, 54
- Strength, at high temperature, 134
 - heat-treating, 91
 - medium and high, heat treatment, 103
 - springs, 116
- Stress, 4
 - allowable working, 14
 - direction of fibers, 50
 - elongation diagram, 4, 9
 - test and reality, 14
- Strike test methods, 24
- Strips, cold-rolled material, 63, 68
 - magnets, 129
 - springs, 116
 - testing of, 121
- Strokes per minute, fatigue tester, 20
- Structure, alloying elements, 42
 - attack of sulphuric acid, 142
- Structure, broken impact test pieces, 19
 - fibrous for springs, 120
 - rapidly cooled pieces, 72
 - heat-treating, 91
 - pressed nuts, 69
- Structural steel, 3
- Substance for case-hardening (*see also* Carburizers), 75
- Sudden blow breakage, fracture, 171
- Sudden drop of scale, beam or dial, 5
- Sudden load test, 14
- Sudden rupture test, work expended, 14
- Suitable annealing temperature, 57, 115
- Suitability of steel for valves, 136, 138
- Sulphur, 3
 - cutting quality, 63
 - dioxide, 142
 - segregation, 47
 - stainless steel, 145
- Sulphuric acid, 142
- Surface condition, durability, 64
- Surface cracks, bars, 56
- Surface hardness, 75
 - air-hardened parts, stainless steel, 143
 - nitrided parts, 90
 - welded parts, 58
- Swivels, 77
- Symbols for steel, standards Germany, 163
 - U. S. A., 153

T

- T (symbol), DIN, 163
- Talbot, 47
- Tamping into boxes, 84
- Tapping operation, melting, 46
- Technical tests, 26
- Te (symbol), DIN, 163
- Teeth, breaking of, 149
- Temper colors, 58, 143
- Temperature, annealing, 111, 115
 - air-hardening steel, 106

- Temperature, carburizing, 75, 85
 - forging air-hardening steel, 106
 - carbon-chromium steel for ball bearings, 124
 - high carbon-chromium steel for valves, 135
 - magnet steel, 130
 - stainless steel, 143
 - hardening steel, ball bearing, 125
 - heat treating, 91
 - tempering, 91, 111
 - melting, 49
 - nitriding, 90
 - pouring ingots, 46, 49
 - recrystallization, 42
 - rolling, analysis, 53
 - salt bath, 86
 - transformation, silchrome, 139
 - toughness and volume of impact test piece, 19
 - valves, 133
- Tempering, air-hardening steels, 106
 - brittleness, 111
 - cause of, 112
 - case-hardened parts, 88
 - heat treatment, 91, 110
- Tempering temperature, influence on
 - annealing brittleness, 112
 - stainless steel, 143
- Tendency to decompose, austenite, 38
- Tensile strength, annealing brittleness, 112
 - Brinell hardness, 24
 - Brinell test impressions, 30
 - notch test, 19
 - test, 4, 14
 - deep drawing material, 68
 - machine, 4
 - tolerance error, 13
 - specimen, 10, 12
 - parts subject to vibrations, 14
 - viscosity-limit, 135
 - welded test specimen, 59
- Test, of materials, 3
- Test specimen, 7, 9
 - annealed material, 51
 - bending test, 10
 - brittle material, 12
- Test specimen, carburizing, 76, 85
 - cross-head, 15
 - cut cross- or lengthwise from ingot, 50
 - ends, 8, 10
 - fatigue test, 21, 77
 - fillets, 10, 12
 - flat, 12
 - flat-rolled stock, 12
 - gage width of, 12
 - heat-treated material, 51
 - impact test, 16
 - length of, sudden load test, 15
 - line of stress, 12
 - location of, in ingot, 50
 - parts over $1\frac{1}{2}$ in. in diameter, 10
 - proper, 10
 - proportional, 11
 - round, 10, 12
 - self-aligning ball, 10
 - sheet metal, 13
 - soft material, 12
 - spherical bearing, 15
 - steel castings, 72
 - strips, 13
 - sudden load test, 15
 - threaded ends, 10
 - turned from large billets, 50
 - undercut, 12
- Testing after annealing, 65
 - ball bearings, 125
 - before annealing, 56
 - case-hardened steel, 75
 - case-hardening bars, 76
 - chromium - nickel case - hardening steel, 80
 - heated specimen, 135
 - ingots, 53
 - inspecting material, DIN, 163
 - machines, limit of size, 77
 - tolerance error, 13
 - welds, 59
- Tests of valve steel, 137, 138
- Tetmayr bending value, 26
- Th (symbol), DIN, 163
- Thermal conductivity, alloy content, 52
 - stainless steel, 143

- Thermal conductivity, valve steel, 134
- Thermocouple, annealing temperature, 57
- Thickness, chromium coat, 147
increase, nitriding, 90
oxide skin, 143
strip for magnets, 129
- Thin carburized layer, 85
- Thin pieces, annealing brittleness, 115
- Thomas, W. B., 64
- Thomas steel, DIN, 163
process, pressed nut material, 69
- Thread cutting, wear on tools, 69
- Threaded ends, test specimen, 10, 11, 15
- Through hardening, 91, 94, 101
large sections, 91, 94, 101
- Throw of crankshaft, 55
- Tight valves, 135
- Time for annealing, 115
carburizing, 85
hardening in salt baths, 86
tempering, 91
heat-treat, 91
spring leaves, 121
testing hot-strength, 135
- Tin, 3, 146
- Tinning sheet metal, 68
- Tolerance error, tensile strength testing machine, 13
machining, ball-bearing steel, 125
- Tool steel, 3, 163
- Tools, 56
- Torch hardening, 87
- Torsion, fatigue break, 169
test, 27
- Total load, 4
- Tough pressed nuts, 69
- Toughness, annealing brittleness, 112
cold-drawn material, change of, with time, 61
decreases, cold-working, 60
heat-treating, 91
spring steel, 116
springs, relation to grain size, 120
stainless steel, 143
velocity of cooling, 112
- Transformation, iron-carbon alloys, 34
point, annealing, 57
temperature, silchrome, 139
to martensite heat-treating, 109
- Transformer, 128
- Transmission gears, 77, 148
- Transmission shafts, 151
- Treatment, melting apparatus, 44
- Troostite, 38, 40
- Trucks, crankshafts, 152
springs, 118
- True hot strength, 135
- True remanence, 132
- Trunnions, 80
- Tungsten, 3
annealing brittleness, 113
influence on structure, 42
steel, 153, 157
for magnets, 130
for valves, 136, 139
- Turned parts, fatigue resistance, 64
- Turning ingots on lathe, 52
- Twinned crystals, austenite, 31
- Twisting cranks, forging crankshafts, 56
- Twisting wire, testing, 27
- U
- Undercut, test specimen, 12
- Undercooling, structure, 38
- Uneven carburizing, 85, 88
- Uniform hardness of balls, 124
- Uniformly soft steel, 56
- Uniform structure, heat-treating, 91
- Uniform temperature after hot-working, 53
- Uniformity, lack of, in cold-drawn steel, 61
- Unit deformation, 4
- Unit forces, 4
- Unit stress, 4
- Unit volume, test piece, 14
- Universal joint, 151
- Universal steels, 104
- Upper transformation point, annealing, 57

Upper yield point, 5
Upsetting eyelets, springs, 116
Upton Lewis testing machine, 123

V

Valve, eccentrically stressed, 135
 for high-compression engines, 142
 for racing cars, 142
 made in two parts, 142
Valve steels, 133
 comparison of, 137, 138
 elastic limit, 135
 yield point, 135
Vanadium, 3
Vanadium steels, 100, 108, 149
 annealing brittleness, 113
Various gage lengths, 7
Varnish, 146
Velocity of carburizing, 84
 of cooling, 111
Vibrations of magnets, 133
 value of tensile strength test, 14
Viscosity limit, 135

W

Walls of castings, annealing, 72
Warping, avoided, nickel steels, 90
 of boxes, 84
 of crankshafts, 152
 of heat-treated parts, 109, 111
Warping oil-hardening steels, 107
Washers, loose, wear-off bolts, 176
Washing parts, electroplating, 82
Water-hardening, heat-treat, 110
Water jackets, 67
Watt losses, 129
Wawrzyniok, Otto, 24, 26, 27
Ways, rustproofing, 146
Wear, abrasives cause of, 147
 of ball-bearings, 126
 of case-hardened parts, 88
 of teeth, twelve years' service, 176
 of tools, 56
 of valves, 138

Wear resistance, of case-hardened parts, 75
 of chromium plating, 147
Weight of chromium-silicon valve, 139
 of ingot, 51
Weisgarber, F., 72
Weldability, composition, 59
Welded valves, 142
Welding, 58
 test, 26
Welds, testing of, 59
Wendt, 91
Werkstoffausschuss des Vereins Deutscher Eisenhüttenleute, 76
Wet grinding of springs, 123
Wheel hubs, 151
Wheel rims, 151
White, 67
White cast iron, 31
Width of springs, 121
Wire, patented, 69
 testing of, 26, 27
Workability, 63
Working condition of valves, 133
 constant, 17
 annealing brittleness, 113
Work expended, sudden rupture test, 14
Work used to break test piece, 16
Working velocity, 17
 annealing brittleness, 113
Working volume, 18
Wrist pins, 151
Wrong heat-treatment, impact test, 19
Wrought iron, history, 1
Wuest, 47

Y

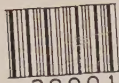
Yellow prussiate of potash, 87
Yield point, 4, 70
 ball-bearing steel, 124
 valve steel, 135

Z

Zink, 146

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